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MATERIALS CHARACTERIZATION AND ECONOMIC CONSIDERATIONS OF COLD-MIX RECYCLED ASPHALT PAVEMENTS

A Report Prepared For The

Highway Extension And Research Project
For Indiana Counties And Cities
(HERPICC)

by

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ABSTRACT

Castedo-Franco, Luis Humberto, PhD., Purdue University, December 1985. "Materials Characterization and Economic Considerations of Cold-Mix Recycled Asphalt Pavements". CoMajor Professors: Leonard E. Wood and Kumares C. Sinha. - Research study sponsored by the Highway Extension and Research Project for Indiana Counties and Cities (HERPICC).

Recycling of asphalt pavements has become a common rehabilitation and maintenance process since the mid 1970s. The state of the art of designing and constructing pavements composed of recycled materials has now advanced to a point where recycling is considered as an alternative to conventional procedures for most paving projects.

An in-depth evaluation of cold-mix recycling techniques was undertaken and the findings are presented in this report. The variability of the existing materials found in city streets and county roads throughout the State of Indiana was evaluated by means of laboratory test procedures. The data obtained from these experiments were statistically analyzed and the results were examined and discussed in an attempt to characterize those pavements. The significance of various factors believed to influence the final performance of cold recycled mixes, was determined by means of extensive sampling of various types of asphalt pavements from counties and cities within the State.

Reclaimed asphalt pavement materials (RAP), with asphalt contents, aggregate gradation, recovered asphalt penetration and viscosity properties, etc., closely resembling values obtained from field-core samples, were used in the laboratory in a series of mix design procedures. These laboratory studies were performed in an attempt to determine the effects that factors such as mixing water, recycling agent content, gradation of the RAP, curing time, etc., will have on the performance of cold recycled mixes produced with existing asphalt pavement materials from Indiana's county roads and city streets.

A detailed analysis and discussion of the main factors that affect the selection and implementation of urban and rural pavements cold recycling, is presented by means of information and findings reported in the literature. A set of guidelines for cold-mix recycling of county roads and city streets asphalt pavements in Indiana, is recommended with the objective of directing and informing county and city engineers of the advantages and disadvantages and potential applications associated with asphalt pavement cold-mix recycling.

CHAPTER 1

INTRODUCTION

Energy crisis (the world-wide increase in the price of petroleum materials), increasing cost and scarcity of pavement construction materials, as well as other factors, have heightened the efforts for conservation and have intensified the search for new methods and processes within the highway construction industry. Economically feasible methods for replacing worn-out pavements have been given little consideration until the early 1970s. Construction and maintenance have been accomplished almost exclusively by using virgin select materials. However, as can be seen in Figure 1.1, recycling of asphalt pavements is often a corrective measure as viable as many common methods used to date, for structural and surface distresses.

Much attention is being paid in recent years to all forms of recycling. Limited resources available for highway maintenance activities often makes recycling the most economic alternative to many highway agencies. However, at the local level (county and/or city highway agencies), a set of guidelines for undertaking a recycling project on a practical sound basis, has not yet been developed.

Current research efforts in highway construction have led to the development of several methods for recycling asphalt pavements. The successful use of these methods may permit:

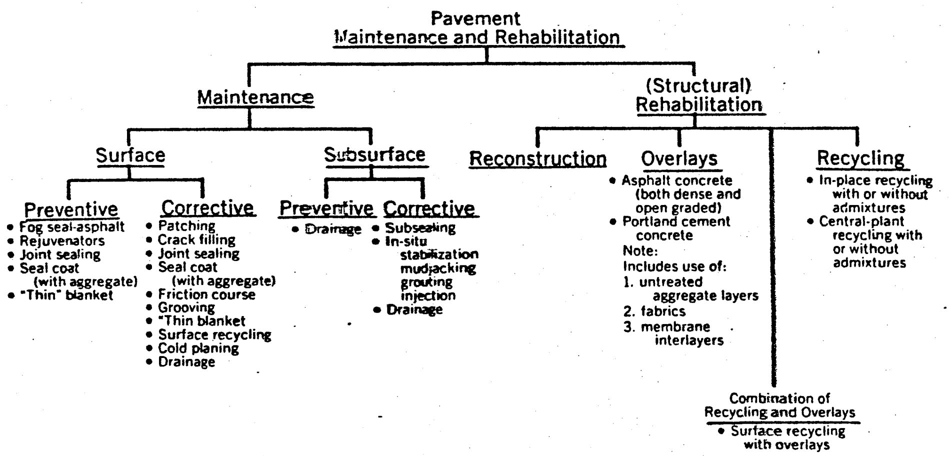


FIGURE 1.1.- PAVEMENT MAINTENANCE AND REHABILITATION ALTERNATIVES (After Monismith, TRB Record No. 700) [93]

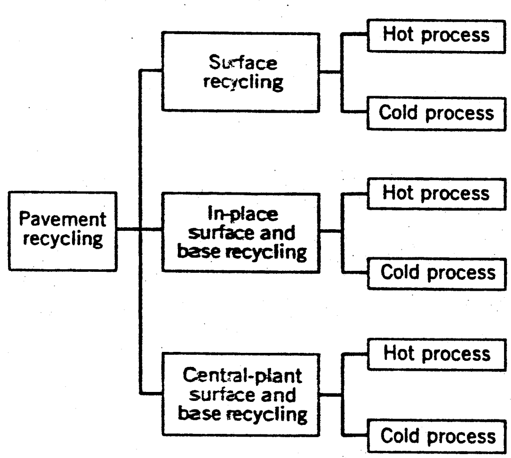


FIGURE 1.2.- ASPHALT PAVEMENT RECYCLING PROCEDURES

1. the use of less asphalt binder and less virgin aggregate
2. a reduction in fuel consumption
3. the correction of existing mix deficiencies
4. the elimination of reflective cracking
5. the increment of the pavement's structural strength without increasing its thickness
6. corrective measures to be taken on exposed base or subbase courses
7. a retention of original curb, inlet and manhole elevations with existing drainage patterns, and
8. a retention of overhead structure clearances.

1.1 - Background Information

Pavement recycling can be categorized by the procedure used, type of materials, and the structural benefit to be gained [1]*. The main forms are: (a) surface recycling, (b) in-place surface and base recycling, and (c) central plant recycling. Most of the operations involved in each of these recycling procedures can be performed either cold (with materials and equipment at ambient temperatures), or hot (Figure 1.2). The difference between cold and hot recycling is the amount of funds, time and other forms of effort that are involved in either process. These recycling procedures are described in more detail in the next chapters of this report.

* Numbers in brackets refer to entries in the List of References

Hot-mix recycling is in general more costly and time consuming than cold-mix recycling. The cold-mix recycling process is selected in most low volume road repair strategies because it is in most cases, the most viable and cost effective maintenance solution for this particular type of road. Factors such as a limited budget and/or the remote location of a particular rehabilitation or maintenance project (far away from central plants), are some common constraints in selecting one method over the other. However, a systematic determination of the maintenance or rehabilitation strategy most appropriate for a given condition should be based on a "pavement condition data" such as the one presented in Table 1.1. Various recycling methods have, nevertheless, many advantages and disadvantages associated with them (see Table 1.2).

County road and city street asphalt pavements in the State of Indiana are wearing out faster than they can be repaired. This situation is worsened by limited funds and scarcity of virgin pavement materials in some locations [43]. A solution whose time has come is to recycle existing pavement materials using bituminous materials and/or rejuvenating agents. Recycling of these asphalt pavements is expected to help stabilize costs, conserve scarce material resources, and reduce energy requirements.

TABLE 1.1.- RECYCLING TECHNIQUES BASED ON ROADWAY CONDITIONS (*)

		TYPE OF DISTRESS																																					
		RUTTING										RAVELING										ALLIGATOR CRACKING										TRANSVERSE CRACKING									
			% AREA										% AREA										%AREA										NO PER STA								
			1-15			16-30			30				1-15			16-30			30				1-5			6-25			25				1-4			5-9			10		
	Recycling Methods Condition of Existing Pavement →	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	NONE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE	SLIGHT	MODERATE	SEVERE
Surface	HEATER PLANER WITHOUT ADDITIONAL AGGREGATE				X			X			X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
	HEATER PLANER WITH ADDITIONAL AGGREGATE				X			X			X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
	HEATER SCARIFY				X			X			X							X			X			X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
	HEATER SCARIFY + THIN OVERLAY																								X	X	X	X	X	X	X				X	X	X	X	X	X	X
	HEATER SCARIFY + THICK OVERLAY																																								
	SURFACE MILLING																						X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X
	SURFACE MILLING + THIN OVERLAY																							X	X	X	X	X	X	X	X				X	X	X	X	X	X	X
	SURFACE MILLING + THICK OVERLAY																																								
In Place	THIN ASPHALT CONCRETE—MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER																								X		X	X	X	X	X										
	THIN ASPHALT CONCRETE—MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER																								X		X	X	X	X	X										
	THIN ASPHALT CONCRETE—MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER																																								
	THIN ASPHALT CONCRETE—MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER																																								
	THICK ASPHALT CONCRETE—MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER																								X		X	X	X	X	X										
	THICK ASPHALT CONCRETE—MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER																								X		X	X	X	X	X										
	THICK ASPHALT CONCRETE—MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER																																								
	THICK ASPHALT CONCRETE—MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER																																								
Central Plant	COLD PROCESS—MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER																								X		X	X	X	X	X										
	COLD PROCESS—MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER																								X		X	X	X	X	X										
	COLD PROCESS—MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER																																								
	COLD PROCESS—MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER																																								
	HOT PROCESS—MINOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER																								X		X	X	X	X	X										
	HOT PROCESS—MINOR STRUCTURAL IMPROVEMENT WITH NEW BINDER																								X		X	X	X	X	X										
	HOT PROCESS—MAJOR STRUCTURAL IMPROVEMENT WITHOUT NEW BINDER																																								
	HOT PROCESS—MAJOR STRUCTURAL IMPROVEMENT WITH NEW BINDER																																								

*After *NCHRP Report 224*

TABLE 1.2.- ADVANTAGES AND DISADVANTAGES OF RECYCLING METHODS (*)

Recycling Categories	*Advantages*	*Disadvantages*
Surface	• Reduces reflection cracking • Promotes bond between old pavement and thin overlay • Provides a transition between new overlay and existing gutter, bridge, pavement, etc. that is resistant to raveling (eliminates feathering) • Reduces localized roughness • Treats a variety of types of pavement distress (raveling, flushing, corrugations, rutting, oxidized pavement, faulting) at a reasonable cost • Improved skid resistance • Minimum disruption to traffic	• Limited structural improvement • Heater-scarification and heater planing have limited effectiveness on rough pavement without multiple passes of equipment • Limited repair of severely flushed or unstable pavements • Some air quality problems • Vegetation close to roadway may be damaged • Mixtures with maximum size aggregates greater than 1-in. cannot be treated with some equipment
In-place	• Significant structural improvements • Treats all types and degrees of pavement distress • Reflection cracking can be eliminated • Frost susceptibility may be improved • Improve ride quality	• Quality control not as good as central plant • Traffic disruption • Pulverization equipment repair requirement • Cost • Cannot be easily performed on PCC pavements
Central-plant	• Significant structural improvements • Good quality control • Treats all types and degrees of pavement distress • Reflection cracking can be eliminated • Improved skid resistance • Frost susceptibility may be improved • Geometrics can be more easily altered • Better control if additional binder and or aggregates must be used • Improve ride quality	• Increased traffic disruption • May have air quality problems at plant site

*From *NCHRP Synthesis 54*

1.2 - Purpose and Scope of Study

The basic goal of this research work was to define the elements required in designing and executing a recycling program for reconstituting low volume asphalt pavements in Indiana's counties, cities and towns. The large variety of pavement materials used in local and rural roads, as well as the lack of information concerning these pavements, increases the technical complexity of the required work. In order to characterize the pavements that could be recycled as well as to evaluate the behavior of the resulting recycled mixes, a combined effort was made in field and laboratory analyses.

First, county roads and city streets were sampled throughout the State in order to obtain representative samples of these types of pavements. Since the cold-mix recycling technique was the method of interest in this study, the pavements surveyed were considered to be potential candidates for cold-mix in-place or plant recycling. The cores obtained were brought to the labortory and they were treated and analyzed as described in Chapter 3 of this report. The sampling locations and other relevant information related to these cores can be found in Reference No. 104. From the initial part of this overall study, detailed information was obtained about parameters of interest such as asphalt content, aggregate gradation, pavement layer thickness, etc.

Second, with the information obtained from the pavement cores described previously, binder contents, gradation ranges, and other parameters, were determined and used in the laboratory to evaluate the performance of cold recycled asphalt mixes. These mixes were prepared with stockpiled materials obtained by ripping and milling operations from four different weathered asphalt pavements. These recycled asphalt pavement (RAP) materials were selected after aggregate sieve analyses and asphalt extraction and recovery tests showed that these parameters were within close range of the ones obtained from field cores.

Using these RAP, that resembled closely the pavement materials found in Indiana, a series of laboratory studies were undertaken to evaluate the effects of what are considered important factors that affect the performance of cold recycled mixes, namely:

- the effect of mixing water, pre-compaction aeration of the mix, compaction effort and the selection of test procedures to carry out this evaluation;
- the effect of new binders and binder content in the performance of the recycled mix;
- the effect of various gradations of the RAP material, from very coarse (as if being the product of just ripping and breaking operations), to a gradation with large amounts of fine RAP;
- the effects of asphalt contents of the weathered pavement material; a RAP material with two artificially aged binder contents (within the asphalt content found for the pavement cores) was used to evaluate these effects.

The main objective of this laboratory and field work was to better understand the complex array of factors and materials involved in the performance of recycled asphalt pavements found in the State of Indiana. Laboratory test results were evaluated using statistical techniques and they were also plotted and tabulated in an attempt to understand the behavior of these mixtures.

An economic evaluation of this rehabilitation technique was attempted by means of cost comparisons with common hot-mix asphalt pavements, and by analyzing savings reported from recycling projects throughout the country. The final objective of this study was the development and recommendation of a set of guidelines to be used by Indiana's county and city highway agencies for cold-mix recycling of asphalt pavements.

CHAPTER 2

REVIEW OF THE LITERATURE

Recycling of asphalt pavements is a highway construction subject that has been the objective of numerous experimental studies and to date it is well documented. There were field applications as well as laboratory investigations sponsored by most of the main highway agencies in the U. S. and abroad (refer to the LIST OF REFERENCES of this report). The literature cites countless examples of all types of asphalt pavements recycling, its economic and materials characterization. However, the State of Indiana, and especially, the local highway agencies have made relatively little use of this rehabilitation process when compared with other state agencies such as Wisconsin and Texas for example.

The objectives of this chapter, and this overall study in general, are to present the information available in the recycling literature, and obtain information that pertains and applies to the pavement types and conditions existent to date, at the county and city levels in the State of Indiana.

2.1 - Recycling of Asphalt Pavements

Recycling existing roads for their asphalt and aggregates content involves tearing up the pavement, trucking it to an asphalt production plant, and recycling it by cold or hot mixing with virgin paving materials (central plant recycling). The old pavement can also be crushed on location and cold mixed with new asphalt without the expense of transporting it to the production plants (in-place recycling). A better alternative involves milling or cold-planing the surface of roads removing only the damaged portion of the pavement (surface recycling). The planer can mill from 2 to 5 inches from pavements with minimum disturbance of traffic flow. The surface can be used immediately or repaved with a thin layer or overlay. The process saves time, labor, and materials.

In any case, recycling can reduce another cost: disposal of the materials removed from a road surface. Before recycling came about, this detritus had to be taken to a dumping site for disposal. The discarded material and cost of trucking represent dollar waste.

2.1.1 Project Selection

Selecting a repaving or repair method should be based on the cause of the road's deterioration. If the road surface alone is affected, cold planing may be the best approach. If deep distress is evident, a portion of the road may have to be rebuilt. Today, many different approaches have been utilized to recycle existing pavements. These methods can be classified into three major areas: (a) surface recycling, (b) in-place recycling, and (c) central plant surface and base recycling (refer to Figure 1.2). The use of heat or not, in these recycling processes, classified them into cold-mix and hot-mix recycling processes. It should be remembered, however, that recycling is only one of several rehabilitation alternatives (see Table 1.1), the selection of which depends upon the observed pavement distress, the establishment of the probable causes of distress based on field and laboratory study, and design input information such as the factors presented in Figure 2.1.

Once this overall preliminary evaluation has resulted in the selection of recycling as the rehabilitation alternative for a particular project, elements such as the ones shown in Figure 2.2 should be evaluated to narrow down the alternatives to a single recycling process that would be the most viable and cost effective among all the alternatives available.

Finally, the performance of the recycled pavement and the determination of in-place material properties should be obtained (if possible), in a uniform and continuous manner for a 20 to 30 year period.

2.1.2 Surface Recycling

Surface Recycling typically deals with the removal of the top few inches of pavement to correct surface defects and improper geometric alignment, removal of heavily "oxidized" crust layers, correction of drainage and city street curbline problems, and preparation of the surface for overlays. This method may be accomplished with or without the addition of heat.

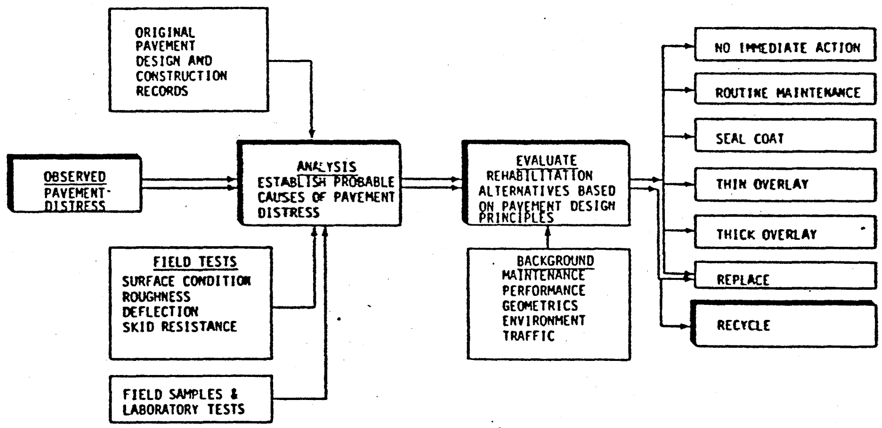


FIGURE 2.1.- RECYCLING AS A REHABILITATION ALTERNATIVE (After Epps, et al., TRB Record No. 780) [3]

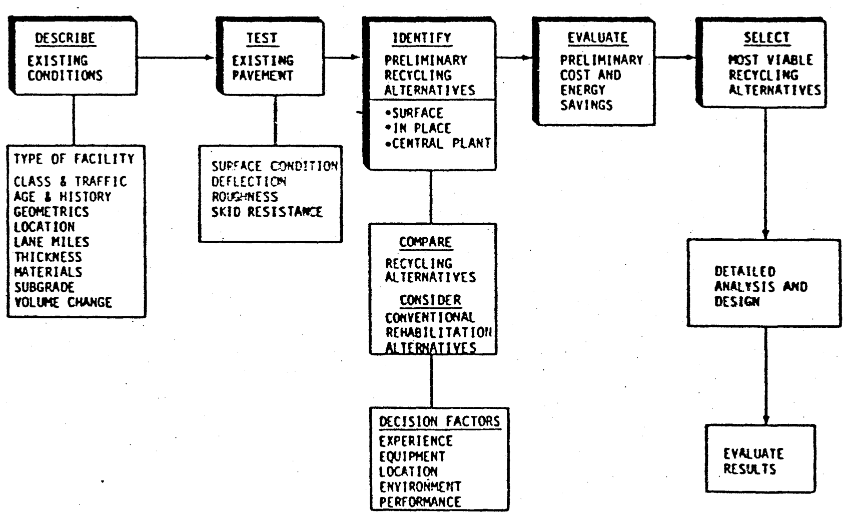


FIGURE 2.2.- PRELIMINARY ANALYSIS AND SELECTION OF MOST SUITABLE ALTERNATIVES (After TRB Record No. 780) [3]

With the use of a heater-planer, approximately 1/2" of pavement is removed with each pass of the machine. The planed material can be immediately laid down as shoulder or base material. The use of heat alters the pavement surface, and thus reduces noise and dust as well as improves the action of the cutters on the milling drum. The cuttings produced this way are about 3/8" in size. They are loaded into trucks to be re-used in shoulders or as base material [7].

Another type of heated surface recycling involves the use of a heater-scarifier. Radiant heat is used to soften the pavement to facilitate scarification without burning the binder. The scarified material is mixed in place with a rejuvenating agent and compacted with a steel wheeled roller. In some cases a thin overlay is then applied [8].

Finally, another method that has been developed for surface recycling uses a grinder-cold planer [7]. The cutting drum has provisions for mounting a varying number of tungsten carbridge tipped bits, to vary the resulting surface pattern to help bond subsequent overlays. The cutting can be used as base course with little or no addition of new asphalt.

2.1.3 In-Place Recycling

In-Place Recycling typically deals with a major reconstruction of the asphalt pavement. All construction processes are accomplished on the job site. The most common application of this method is to rip up the existing pavement to form a stabilized base. A thin overlay, in the order of 1.0 to 2.0 inches or the application of a chip coat completes the operation. Some of the methods used to break the pavement are the traveling hammer mill and the pulverizer-mixer machines [7]. Typical in-place surface and base recycling operations are depicted in Figure 2.3.

2.1.4 Central Plant Recycling

Central Plant Recycling uses discarded asphaltic concrete as well as material presently serving as pavement, as the raw material in the production of recycled mixes. Existing pavements that are to be rehabilitated are ripped up and either crushed in place or transported to a central plant for crushing. Rubble piles of old asphalt pavements can also be used.

Aggregate gradation problems can be corrected with the addition of appropriate sized aggregates. In most cases, a small percentage of virgin make-up asphalt is needed. The end product is used as any conventional asphalt paving mix can be used. The central operations may involve the use of heat, or it may be a cold mix operation using cutbacks or emulsions.

Wisconsin's experience with recycled asphalt paving materials has led them to prefer the hot-mix method [3]. For this method, the whole pavement is ripped up or just the top few inches are milled off. The removed material is taken to a nearby asphalt hot-mix production plant where it is mixed with new binder and virgin aggregate, in varying proportions.

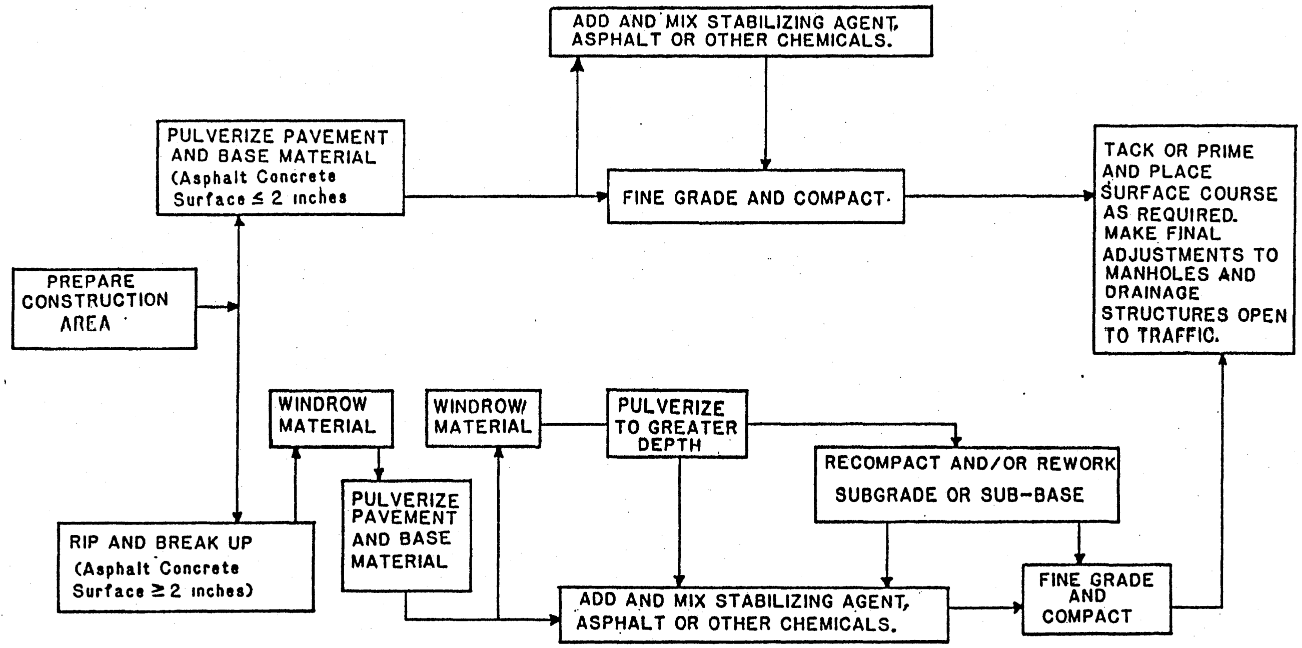


FIGURE 2.3.- COLD IN-PLACE SURFACE AND BASE RECYCLING OPERATIONS
(After NCHRP Report No. 224) [15]

This method reduces costs savings and other economic advantages. The salvaged materials have to be hauled to a mixing plant and have to be heated to about the same temperatures used for new hot mix to obtain a homogeneous product. Both processes require energy. However, the so-called "Minnesota Heat-Transfer" method for recycling bituminous pavements has proved to be less energy consuming than conventional hot-mix operations, and produces recycled mixes comparable with conventional full-depth asphalt base course mixes [9].

Wisconsin, Minnesota, and many other state highway agencies where pavement surfaces are continuously subjected to extreme temperatures and severe weather, have found that the quality and homogeneity of the mix produced by the hot-mix central plant recycling process is essential. They found that using the same on-site cold-mix recycling methods used by Texas and other hot and dry weather state highway agencies, could not give them the quality control needed for road surface durability in their climate, especially on roads with heavy traffic flow.

The use of cold-mix techniques, makes homogeneity of the mix difficult to obtain right away, because the aged binder and the virgin binder or rejuvenating agent do not combine immediately after mixing. A central plant hot-mix pavement, is often stronger and more durable since the mix can be controlled and improved during recycling.

Each of the recycling methods described above have advantages and disadvantages (refer to Table 1.2 in Chapter 1).

However, all of them, as a common characteristic, are efficient in the conservation of virgin asphalt and new aggregate supplies. In most cases, the reduction or elimination of pollution problems is also achieved. From the economic point of view, all methods are reported to have resulted in cost savings when compared to conventional virgin asphalt mixes.

The large energy demand of the heater-planer, the heater-scarifier, and the hot-mix central plant recycling methods, is a common cost related problem. Air pollution and hauling requirements are also disadvantages of the central plant recycling (cold or hot processes). A solution to the pollution and energy requirements problem would be the use of a cold mix operation.

2.2 - Urban Cold-Mix Recycling Process

The work to be performed on urban and rural roads is somewhat different because of differences in grade control, obstruction, traffic, access to adjacent property, and other factors. The size and magnitude of the urban projects are generally smaller in scope. Also there are many more physical constraints such as curbs and gutters, catch basins, driveways, cross gutters, median curbs, manholes, etc.

Project Selection:

According to Vicelja [12] and Canessa [13], an urban project can be a candidate for recycling even if the project's size is very small (1/10 to 1/4 mile, or a typical city block). However, the economical end environmental potential through recycling, must be evaluated for each particular job. If the economics are not favorable, the removed asphalt concrete can still be utilized on a future project by stockpiling it, thus conserving natural resources and fuel.

In the urban environment most of the roads and streets are improved with curb and gutters, catch basins, etc. As mentioned before, these street elements control the geometric and horizontal alignment and many times also provide the vertical control for finished pavement elevation. These types of controls can create considerable problems when designing and placing a thick asphalt concrete overlay.

Some of the typical problems resulting from thick overlays are: (a) excessive crossfall, i.e., car doors cannot be completely opened (passenger side door); (b) ridability of cross gutters and (c) driveway access (both gutters and driveways eventually have a considerable drop-off); (d) reduced water carrying capacity when storm run-off either tops the curb or extends further out into the traveled portion of the roadway than originally designed; (e) loss of height of median barrier curbs; and (f) raising of manholes or utility vaults. Recycling the existing asphalt concrete pavement can reduce the magnitude or eliminate some of these problems.

Traffic Control and Other Considerations:

When evaluating a project and determining if recycling should be used, project location often limits the techniques available when working in a central business district, industrial or residential area [12]. Traffic control considerations which must be evaluated are: requirements of a detour route, and whether construction can proceed utilizing a portion of the existing roadway or if the street can be closed during construction.

A good public relations attitude by the local highway agency requires the determination of the effects that the increased dust and noise will have on the adjacent properties, when selecting in-place versus off-site recycling techniques. With the equipment available today, in-place cold-mix or surface recycling can be accomplished in most urban areas without adversely affecting the environment [14, 15].

The location of existing asphalt batch plants (central plant cold recycling) or material storage areas for the RAP must be included as part of the economic study when determining fuel, aggregate and paving asphalt cost-savings through the use of recycled materials.

Presentations should be made to local officials, planners and citizens showing that the benefits of recycling outweigh any inconveniences a few may encounter. Local contractors should be encouraged to obtain the equipment needed for recycling by demonstrating that it is economical and beneficial. They should also be informed of the local highway agency's intention to further utilize this construction technique.

Pavement Analysis and Urban Cold Recycling Construction:

It has been demonstrated that if the project has only localized areas of distress, recycling can be used in the distressed areas and then an overlay or a surface treatment can be placed to complete the work. When localized failures occur only in the surface portion of the structural section, cold planning or milling out a portion of the asphalt pavement can make an economical repair with recycled asphalt concrete. In addition to the benefits already mentioned, the replacement of the removed pavement material by new asphalt concrete mix has proven effective in business districts and industrial areas.

Work usually can begin on the traffic lanes after the morning peak traffic, and be completed and ready for use in time for the evening rush hour. This eliminates the need to barricade off a portion of the roadway or detouring traffic around the project.

The distress in the pavement, when related to the untreated base material, can be structurally improved by recycling the asphalt concrete surface and parts of the untreated base into an asphalt concrete mixture. Thus, the structural value and load carrying capacity of the pavement can be increased considerably with no increase in thickness or change in grade.

On the other hand, if an urban roadway is structurally adequate but has developed significant amounts of cracking due to aging, its integrity and ridability can be improved through recycling. It is also possible to reprofile a street with recycling. These generally can be accomplished through surface recycling techniques, however, cold recycling can also be used if a considerable depth of asphalt concrete is to be removed.

Economic Analysis:

The use of urban cold recycling must be approached in the same manner that an overlay or new construction project is evaluated. That is, the project must be planned, programmed and scheduled to take maximum advantage of available economics. Many urban maintenance and rehabilitation projects which would be postponed due to shortage of funding, thus leading to further deterioration, can be effectively rehabilitated at a lesser cost by using cold-mix recycling. Typical economic analyses for small urban cold-mix recycling projects are presented and discussed in detail in Chapter 5 of this report.

2.3 - Rural Cold-Mix Recycling Process

Rural and urban construction environments are different in nature. The factors involved in pavement construction have different effects on the end product of the highway construction industry in general, depending on what environment they are performed on. Nevertheless, the cold recycling operations performed in rural roads have to meet specified requirements such as the ones designed for any other type of roadway pavement.

Traffic control, safety, noise and air pollution control are handled differently; road-side vegetation damage, as well as long hauling distances, are factors found mainly in rural cold recycling operations. The materials that form the asphalt pavements in these two environments do not differ greatly in their composition. Variability among the various layers that constitute the same roadway pavement was found to be larger than the variability that exists among city street and rural road pavements. Rural and urban cold recycling operations can be best compared in a summary way, as presented in Table 2.1.

2.4 - General Factors Involved in Cold-Mix Recycling

Besides the materials composition and structural factors involved in cold recycling operations, there are cost, energy and other related factors involved in this type of highway construction operation.

Environment:

Environment-related factors are an important part of the recycling operations. The largest contribution to the environment comes from re-using materials that previously were discarded in landfills. The re-use of these materials reduces the depletion of aggregate and asphalt sources, and the manufacturing efforts and resources that would have been invested in new materials.

TABLE 2.1.- COMPARISON OF RURAL AND URBAN RECYCLING PROJECTS - SELECTION CRITERIA (After TRB Record No. 780) [4]

Item	Rural	Urban
Vertical Control:	Shoulders, bridges, safety accessories.	Utilities, drainage structures, safety app.
Traffic Control:	More options.	Major problems.
Road User Costs:	Do not always dominate project cost.	Dominates project cost.
Time for Construction:	Not as critical.	Critical
Size of Project:	Large projects because of move-in cost.	Plants and equipment move-in cost minimal.
Environmental Quality:	Not as many complaints on noise, heat, air quality, vegetation damage. Permits to operate plants require up to 6 months to obtain.	Critical but existing plants have permits.
Aggregate/Binder:	Fixed and new sources.	Fixed sources.
Contractor Availability:	Most contractors prefer to work in rural areas.	More competition.
Existing Pavements:	Non-hard surfaced, thin surfaced.	Thicker asphalt sections.
Specifications:	Lower quality matl's; Single project approach.	High quality matl's. Multiple proj. app.

Contractor Availability:

Contractor availability is a necessary consideration in the selection of recycling as a rehabilitation alternative. The engineer or highway agency needs to be sure that there are contractors in the area who are prepared to bid on a recycling project.

In general, contractors for surface recycling are more readily available than those for in-place cold recycling [17]. The equipment for surface recycling is portable and can be moved over larger distances quickly. As the volume of work increases, contractors can station more equipment in central locations and provide more competition in all areas. Contractors with the proper type of equipment for cold in-place recycling are somewhat more limited when compared with surface recycling; however, they are available.

It is believed that if more agencies in a particular area would specify in-place recycling, contractors would acquire the equipment which in turn would create a more competitive situation. There are many examples in the literature of relatively small projects in which only one contractor bid on it. It also happens that due to the fact that contractors do not have the proper equipment, the recycling contract is cancelled and subsequently awarded using a more conventional design [17]. However, if the project is sufficiently large the contractor can afford to bring in the proper equipment.

Many parts of the country have only a limited number of contractors for central plant recycling except for large projects, frequently they are located only in large cities where recycling projects of this kind are more common [48].

In summary, contractors for surface recycling are available in most parts of the country and competitive conditions exist in most cases. The availability of contractors for in-place and central plant, on the other hand, is somewhat limited to the size of the project. To improve the contractor availability for the various types of cold-mix recycling rehabilitation procedures, a continuous and dependable market for recycling materials must be present at the State and local highway agency levels.

Cost and Energy Factors:

Savings in a cold recycling operation are realized by comparing the initial cost of the various common alternatives to those of a recycling process. From a particular project in Oregon [18], it was reported that these savings can approach $ 1 million per 15-mile project, depending on what type of conventional rehabilitation technique cold recycling is compared to. The material is applied at ambient temperature; therefore, the fuel cost to heat conventional mix to 300 deg.F is eliminated. Because the mix is not heated, there is no need for emission control or paving plant equipment. Recycling eliminates the need to mine, crush, and screen aggregates. Also, because the existing pavement material contains 5 to 6% asphalt, the addition of liquid asphalt can be reduced from the normal 6% to 2% or less. Hauling costs, which can represent an important part of the total project cost depending on the location of the job, are totally eliminated.

The conservation and cost savings in energy required by the recycling of asphalt pavements in general, is by far one of the most important qualities of this rehabilitation process. The simple fact that vast quantities of asphalt and aggregates accumulated over decades of pavement construction can be re-used implies that energy requirements to manufacture new binders and virgin aggregates can be eliminated. There are more than two million miles of paved roads in the U. S., representing a vast storehouse of paving material that can be recycled.

Variability of Asphalt Pavement Materials:

In most urban and secondary rural roads, the indication that there are numerous and variable components that form the pavement structure, is evident. In most cases a simple visual inspection will determine this fact. Construction and routine maintenance records are usually nonexistent, and traffic loads as well as varying climatic and terrain conditions affect asphalt pavements in so many different ways that the most safe and sound approach to be taken for planning, designing and implementing a recycling job, is on the one-by-one basis.

Each individual project should be analyzed and planned with the maximum permissible amount of effort and expertise available. It is essential to evaluate the properties of the materials to be recycled in order to determine the process and equipment to be used to remove it, as well as the aggregate and recycling agent types (if any) that must be used to modify them to meet specification requirements.

Construction Practices:

Large variation in aggregate gradation and asphalt content of the recycled mix is undesirable for a good performing paving mix. Construction procedures adopted during the salvaging operation and throughout the recycling process help to minimize the amount of variability of these types of mixtures. Besides initial surveys and sampling of the material, consistent cold milling operations, planned stockpiling (for central plant cold-mix recycling), and constant monitoring of the recycling mix process, will ensure a high quality recycled mix.

Brown [31] and others [32, 33] reported that the average standard deviation of the aggregate gradation and asphalt content for recycled asphalt mixtures is in general greater than those for new asphalt concrete. One of the first steps to minimize variability would be to control the cold milling or existing pavement removal operation. The speed of travel must be constant, the cutting teeth should be maintained in good condition, and the depth of cut must remain the same so that the resulting aggregate gradation is more uniform. Multipass methods can be used to remove each one of the existing layers of asphalt material when they vary considerably in thickness and material composition.

Another step to reduce mix variability during the construction process is to improve the handling of the reclaimed material. This material is either reworked in-place from a windrow or stockpiled for later use. The proper amount of remixing to obtain a more uniform material in terms of asphalt content and gradation can be achieved by moving the material with a motor grader or similar equipment from one place to another. If remixing is not possible, then materials of significantly different composition should be placed in separate stockpiles and/or treated in separate sections of the in-place operation with a separate mix design prepared for each.

The final and less practical step that can be used to reduce variability is the constant monitoring of the mix being produced. Frequent testing will allow frequent adjustments to the asphalt contents and aggregate gradation, which in turn should reduce variability. However, as the construction sequence presented in Figure 2.4 shows, this is almost impossible to achieve in a cold in-place recycling operation. Constant monitoring of the mix produced is feasible only when central plant processing is being used.

Construction procedures for recycling county roads and city streets in Indiana can be accomplished following the operational sequence shown in Figures 2.3 and 2.4. Nevertheless, whatever the sequence of operations used in cold recycling, the major operations consist of: pulverization; adding and mixing water and/or recycling agents; fine grading, compaction and curing of the recycled mix.

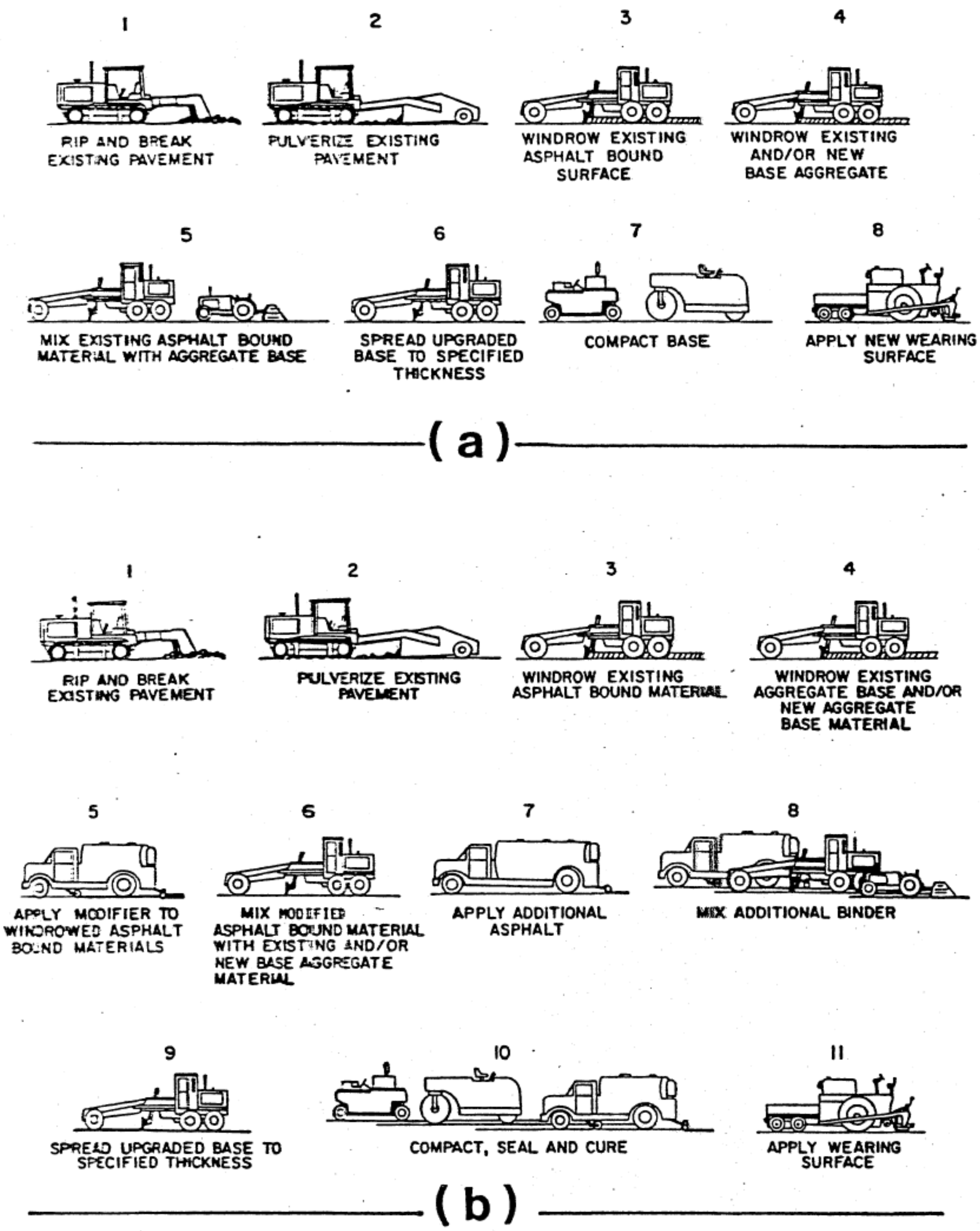


FIGURE 2.4.- TYPICAL IN-PLACE COLD RECYCLING OPERATION (a) WITHOUT, AND (b) WITH RECYCLING AGENT ADDED (After NCHRP Report No. 224) [15]

Excellent information on cold recycling construction operations can be found in References 6, 7, 15, 17, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, and the publications related to the FHWA Demonstration Program No. 39 [19 to 30].

Quality Control and Other Considerations:

The control of a number of construction details is important to produce a satisfactory cold recycled mixture. For surface recycling the most important aspect is to achieve the design depths of scarification and to add the proper amount of recycling agent to this total depth.

Weather considerations are important for any type of cold recycling procedure and depend on the time of year when recycling is performed. The summer season does not generally pose special problems. Care needs to be taken to stop construction early in the day if cool nights (60 deg.F or less) are expected. The temperature becomes more critical if a mixture with large amounts of fines is encountered. Such mixtures retard the evaporation process of the mixing water and/or volatile constituents of the recycling agent and increase curing time.

Finally, the objective of in-place or any other cold-mix recycling technique, is to obtain a thorough mixture of a pulverized existing pavement material (with or without new aggregate), with the correct amounts of recycling agent or stabilizer material (if used), and sufficient fluids to obtain maximum density during compaction. To achieve these ends, construction equipment and procedures must be selected, operated and sequenced to provide the following: (a) pulverization of the recycled pavement material, (b) proper water content uniformly mixed, (c) proper recycling agent content (uniformly mixed); (d) achievement of some minimum specified density, (e) favorable temperatures and moisture conditions for strength development during the curing period, and (f) protection of the recycled surface from traffic to prevent abrasion and to ensure adequate time for strength development.

Salvaged Material Policies and Regulations:

The entity responsible for producing the recycling mix should be responsible for the removal, processing and recycling of the salvaged materials [48]. Experience has shown that this is the best way to ensure the quality of the pavement removed. Deleterious and objectionable materials are often found contaminating the salvaged pavement material; thus, the quality of the end product is inferior and there is a large potential for premature failure of the recycled pavement.

Even though, this is more of a problem for central plant processed recycled mixtures, the fact that there are no proper specifications written for the removal of the existing pavement itself, gives room for the often common thought in those individuals involved in the construction process that an inferior product must be accepted. The bidding procedure for a recycling project should be such that the responsibility for the quality of the RAP material lies with the contractor responsible for the quality of the final cold recycled pavement.

Government regulations related to safety, noise and air pollution, can be of some concern when using recycling procedures. Safety regulations require the handling of traffic and other factors, much in the same way as in any highway maintenance and rehabilitation process. Air and noise pollution problems are of no major concern with central plant recycling operations; however, cold and hot milling of existing pavements for cold recycling in general, do produce some questionable levels of dust and noise. The use of water during the cutting operation helps to minimize dust; noise on the other hand, seems to be of a lesser concern in rural environments when compared with cold milling operations in urban areas; equipment design is the best solution found to reduce the noise problem.

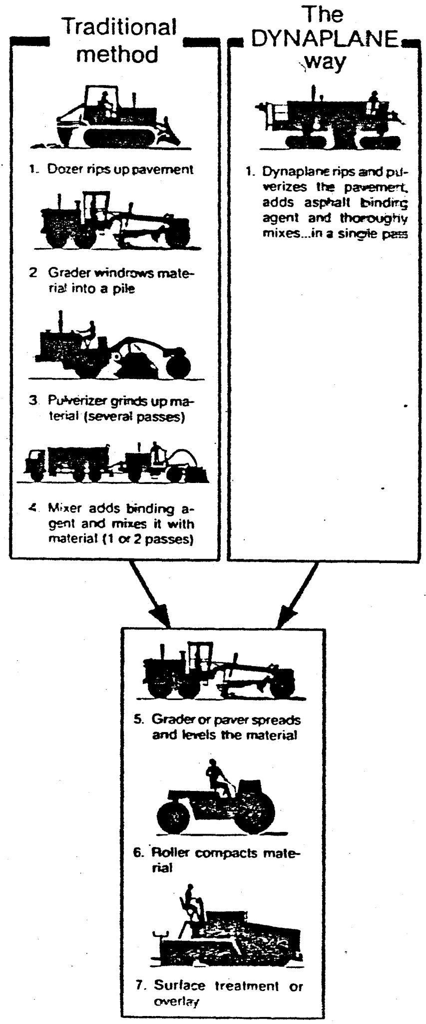
2.5 - Equipment for Cold Recycling of Asphalt Pavements

Equipment is an important component of the recycling operation. It must not only be cost-effective but compatible with manpower availability and the type of material to be recycled. A search of the available literature indicates that vast amounts of information have been published by the equipment manufacturers as well as by technical reports of field applications throughout the country. The basic cold recycling techniques are, in general, accomplished with the use of existing soil stabilization or on-grade stabilization equipment, with the only specialized equipment being that used to properly size the salvaged material prior to stabilization [15].

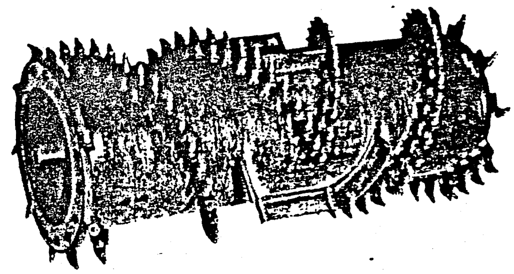
Development of pulverization and pavement removal equipment in recent years has greatly contributed to the economic viability of cold recycling operations. The main pieces of equipment that use additional heat for removing and pulverizing the original pavement material, are: heater planers, heater scarifiers, and hot millers. Equipment for processing with no additional heat are: cold planer, cold miller, pavement rippers, traveling hammermills, and improved soil stabilization equipment [10].

The general procedure of cold in-place recycling is depicted in Figure 2.4, where the various pieces of equipment used can be readily seen. The reclaiming of the existing pavement, in particular, has improved in recent years with the advent of the profiler, miller or planer. Now, material can be recovered and loaded into haul units with a single machine (see Figure 2.5-d) for central plant operation or stockpiling purposes. Full- or half-lane width cutting can be obtained with cold planers equipped with cutting drums such as the one shown in Figure 2.5 (b).

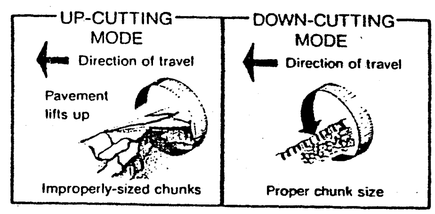
For partial depth cold recycling the standard up-cutting mode of operation (Figure 2.5-c) offers the best control of material sizing and ensures proper end results. When the entire pavement section or combination of underlying base aggregate is



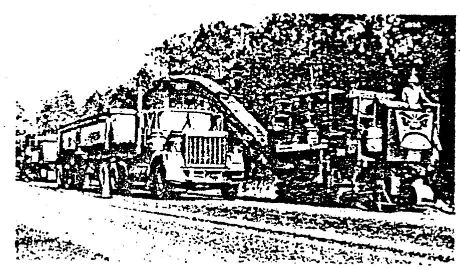
(a)



(b)



(c)



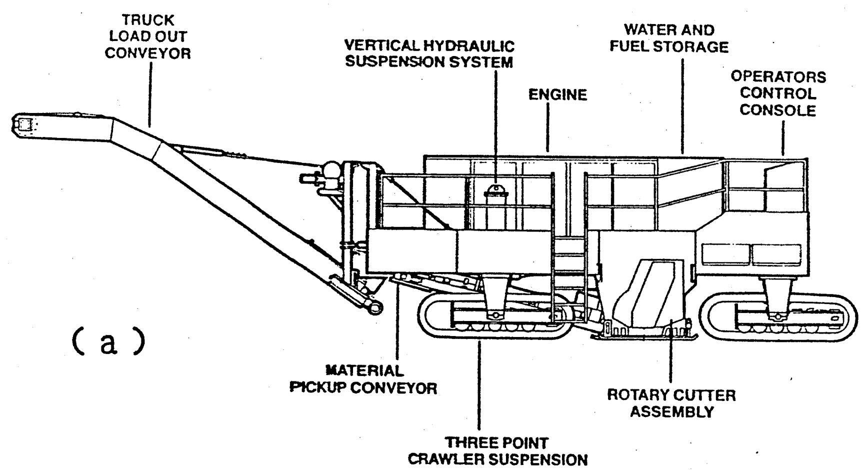
(d)

FIGURE 2. 5.- COLD-MIX RECYCLING METHODS:
(a) DYNAPLANE (Barber-Greene) VS. TRADITIONAL COLD IN-PLACE RECYCLING METHOD; (b) MT-6520 CUTTER DRUM (Ingersoll-Rand); (c) BI-DIRECTIONAL CUTTING MODE: RX-40 & RX-80 MECHANICAL CUTTERS (Barber-Greene); (d) RX-40 DYNAPLANE IN OPERATION (Barber-Greene)

pulverized, it is required that the machine operates in the down-cutting mode (Figure 2.5-c), so that pavement materials can be crushed against the aggregate base, resulting in proper sizing [14].

There are many variations of the soil stabilization and cold in-place recycling operating systems available in the market today. When the type of recycling process has been selected for a particular project, the availability in the region of one brand of equipment over another is most likely to be the deciding factor in selecting the machine to be used in the recycling operation. However, improved equipment such as the one presented in Figure 2.5 (a), helps to reduce the amount of equipment, manpower and necessary steps required to handle cold recycling jobs, thus increasing the cost-effectiveness of this rehabilitation technique.

The components of this one-pass, in-place cold recycling machine, as well as the system used to add the necessary recycling agent and/or new liquid binder, are depicted in Figure 2.6 (a) and 2.6 (b), respectively. This type of equipment and recycling process (single pass operation), is a real advantage for urban cold recycling operations since it minimizes traffic disruption by operating in one lane at a time, allowing traffic to flow freely in the other lane. For more detail on these equipment and their operating characteristics, the interested reader is directed to References No. [7, 10, 14, 18].



(a)

DYNAPLANE COMPONENTS

(b)

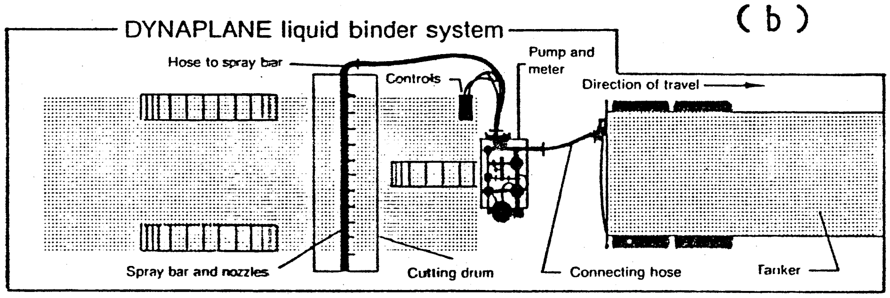
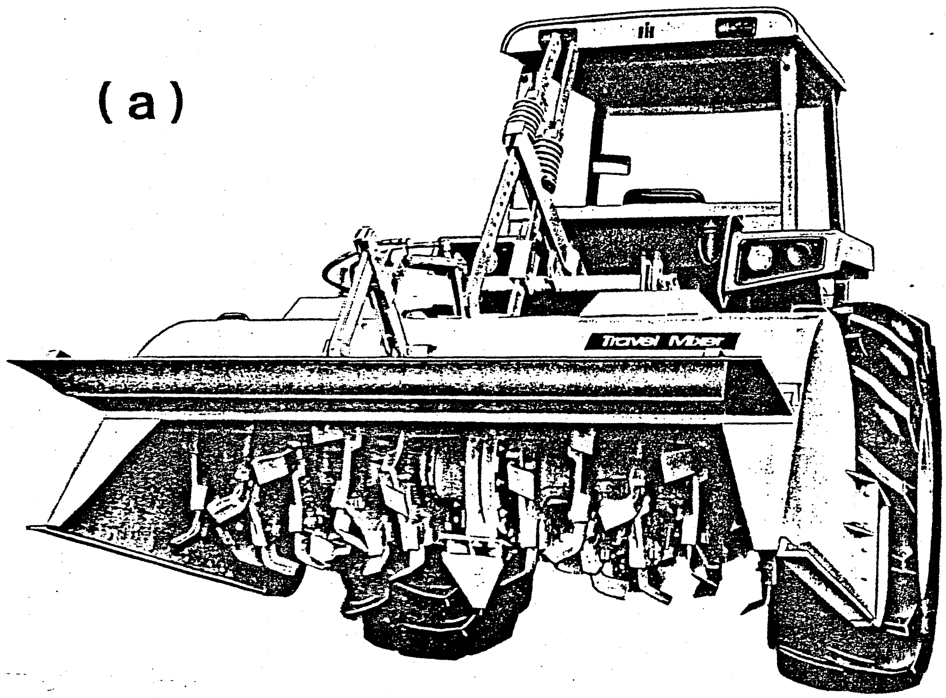


FIGURE 2. 6.- COLD MILLING EQUIPMENT:
(a) DYNAPLANE COMPONENTS (Barber-Greene), AND
(b) DYNAPLANE LIQUID BINDER SYSTEM (Barber-Greene)

Figure 2.7 (a) depicts another common in-place recycling system: the travel mixer used for in-place, low-cost stabilizing of recycled asphalt pavement materials. This type of machine is widely used for recycling county roads and low volume roads. Oversized reclaimed material used to be of major concern with this type of equipment; 4-in. or even 6-in. chunks constituted from 5 to 10% of the salvaged material [18]. This was not conducive to paving; as neither proper compaction, nor proper distribution of a liquid additive could be achieved. The addition of the two-stage sizing and mixing feature (Figure 2.7-b), converts a standard cold milling machine into a high production, accurately controlled, in-place recycling machine, where the oversized material passes through the small crusher for further processing to a specified size and for thorough mixing.

Finally, cold milling equipment (Figures 2.5 and 2.6) can be used for profiling (to re-establish the true line and grade) old, rutted, and/or out of grade asphalt pavements, instead of using a leveling course. The rate of milling for these machines can be obtained from Figure 2.8 for various depths of cut at temperatures of 50 deg.F or above. Excellent information on cold recycling construction equipment can be found in References 7, 14, 15, 34, 43, 50, 55, 56, 57 and in the reports from FHWA Demonstration Project No. 39 [19 to 30].

(a)



(b)

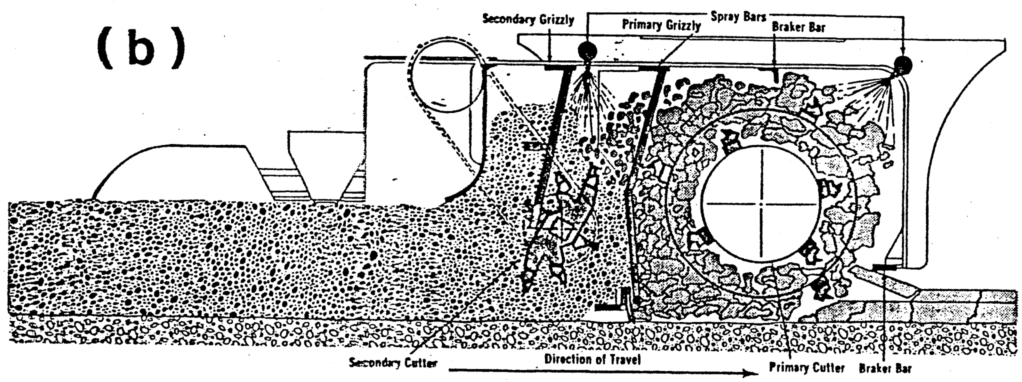


FIGURE 2.7 .- IN-PLACE COLD-MIX RECYCLING EQUIPMENT:
(a) T.O.-730-H HYDROSTATIC TRAVEL MIXER (Seaman-Maxon),
(b) PR-450 ROTO-MIXER (CMI Corporation)

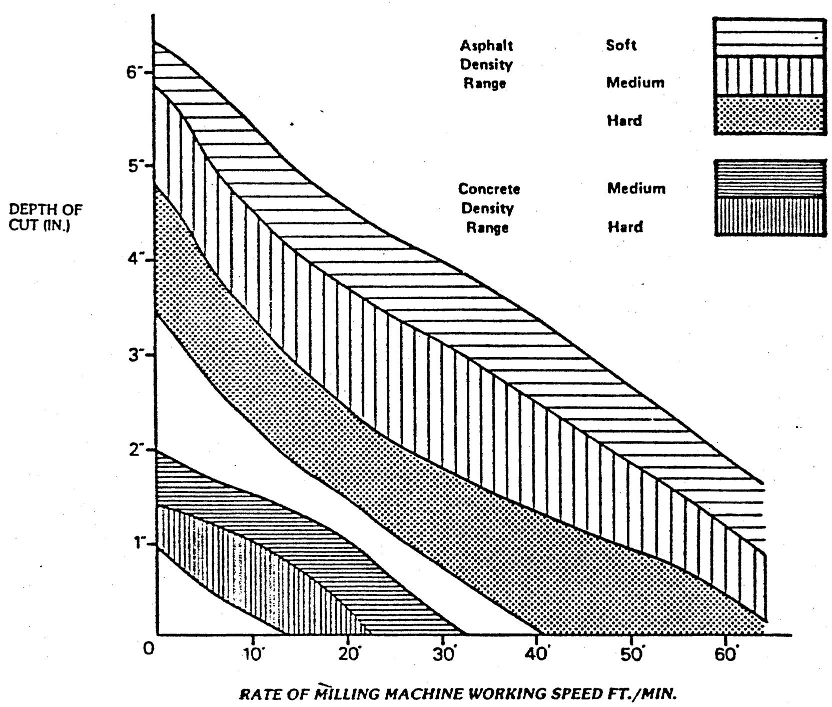


Chart scale is based on milling asphalt at 10°C or 50°F or above. Below this temperature the speed of milling will fall perceptively.
Because of the variety of penetration asphalts used, the effect of temperature drop on production in a given material is difficult to predict, but a drop of 20 percent per 10 degrees would not be unusual.

FIGURE 2.8 .- RATE OF MILLING VS. DEPTH OF CUT FOR COLD MILLING MACHINE (After Reference No. 14)

CHAPTER 3

INDIANA'S COUNTY ROADS AND CITY STREETS MATERIALS CHARACTERIZATION

It is highly likely that existing asphalt pavements to be recycled will consist of layers of asphalt concrete of different composition, or road mixes or surface treatments having different characteristics. Similarly, existing stockpiles of salvaged material may have been obtained from pavements that also have different characteristics. It is likely that a length of pavement selected for recycling can vary in materials composition from one end to the other.

These variations could result from normal construction practices, normal maintenance practice, or weather and pavement age variations. Test data from samples obtained from highly cracked areas may display different properties than test samples taken from uncracked areas of the same asphalt pavement. Variability introduced by these characteristics may be high in many cases. On the other hand, some pavements can be relatively uniform throughout the test section being analyzed.

Pavement cores were taken from different county roads and city streets throughout the State of Indiana with the specific purpose of obtaining materials for laboratory testing and evaluation. It was expected to obtain from this analysis, information that would aid in the creation of a practical and realistic set of guidelines for the recycling of asphalt pavements in Indiana counties and cities.

The entire network of county roads and city streets of Indiana was the inference population of this evaluation. The State was divided into three separate geographical and climatological regions (see Table 3.1); in each one of these regions a group of county roads and city streets was sampled and the cores obtained were taken to the laboratory for testing.

This procedure was adopted mainly due to the lack of information available on the existing pavement materials from the respective highway agencies. The methods used to obtain this information, as well as the data collected are described in the next sections.

3.1 - Sampling Procedure and Locations

A portable drill with a 4.0 inch diameter bit was used to obtain the pavement cores. Figures 3.1 and 3.2 respectively, show the different locations where county roads and city streets were sampled. These locations were selected on the bases of:

a.) their geographical distribution in the State (northern, central and southern part of Indiana),

b.) their potential for recycling (pavements with extensive deterioration and in need of immediate repair),

c.) their volume and type of traffic; farm to market as well as suburban pavements were considered,

TABLE 3.1.- CLIMATOLOGICAL AND GEOGRAPHICAL REGIONS (INDIANA)

Region:	Northern	Central	Southern
Counties:	Elkhart (1)*	Tippecanoe (4)	Monroe (7)
	Lake (2)	Montgomery (5)	Warrick (8)
	White (3)	Hamilton (6)	
Cities:	Goshen (9)	Laf./W.Lafayette (11)	Bloomington (13)
	Lowell (10)	Noblesville (12)	Boonesville (14)

* Coded Zone Number.

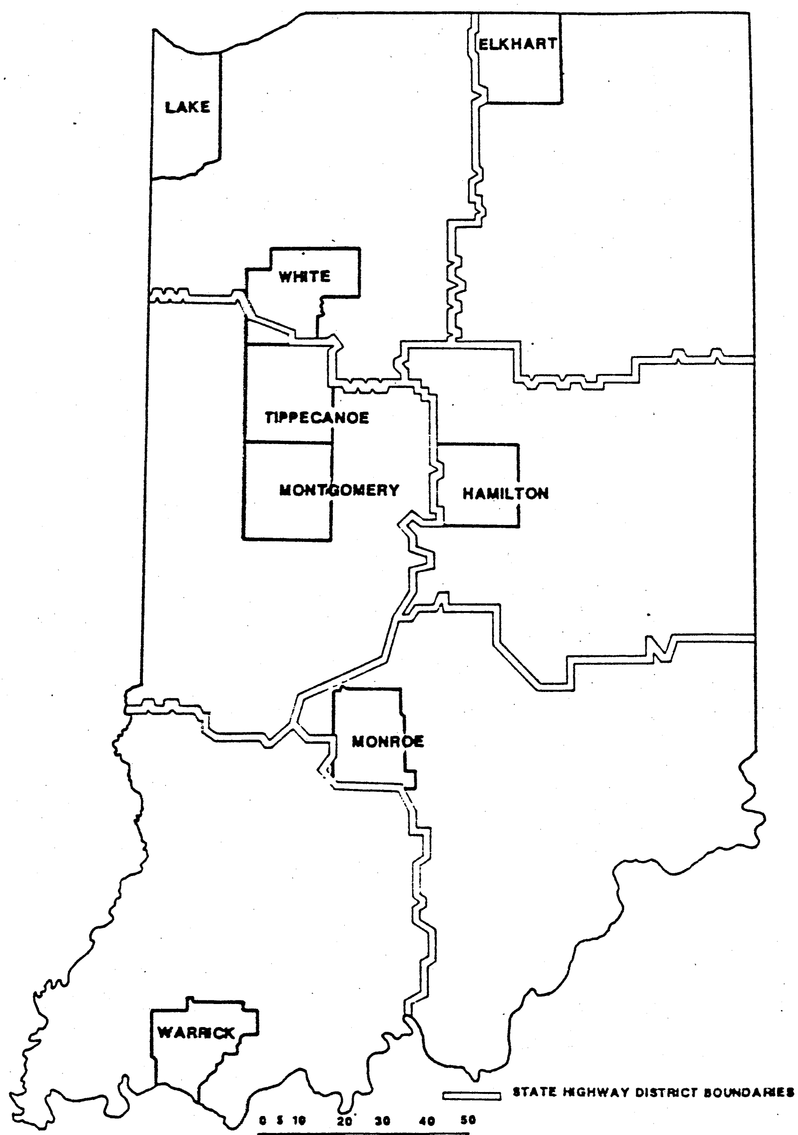


FIGURE 3.1.- COUNTY ROADS LOCATIONS

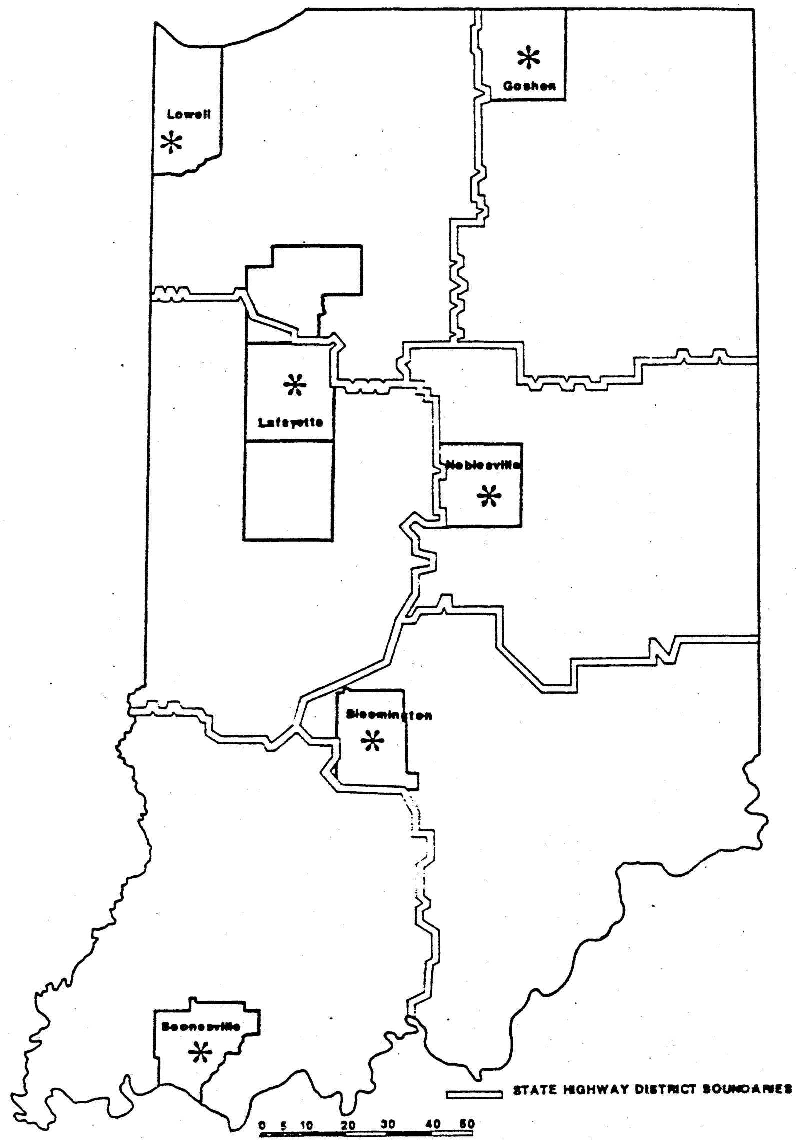


FIGURE 3.2.- CITY STREETS LOCATIONS

d.) and their typical characteristics; by initial discussion with the local highway engineer and visual in-site inspection, the selected road was considered as being a representative pavement section of that particular county or city.

All the pavements selected for sampling were considered to form a realistic group of county roads and city streets representative of these type of pavements in the State of Indiana. The number of samples collected as well as the locations and parameters measured were believed to give a statistically sound representation of these asphalt pavements and the materials of which they were constituted.

The widest possible spectrum of pavement types found in Indiana's counties and cities was considered for sampling: hot laid plant mix, cold laid plant mix, road mix, patched pavements as well as various types of surface treated asphalt pavements.

The data obtained from these pavement cores were used in statistical analyses in order to determine: (i) the extent of the existing variability among pavements throughout the State, (ii) the extent of the variability within pavement sections, and among others, (iii) to identify the main factors that are responsible for this variability.

3.2 - Tests Performed on Pavement Cores

The pavement cores obtained from the locations described previously were subjected to a series of laboratory tests in order to obtain data for the response variables used in the statistical analysis. The various test measurements were as follows:

1. The cores representing various pavement layers, were weighed in air, and the height of each layer was measured and recorded.

2. The cores were sliced (along their diameter) into smaller samples representing the individual layers that formed each particular pavement core. There were between 1 and 4 layers in each core.

3. From each sliced layer the following information was obtained:

   a. Specific gravity (density) of the layer by means of ASTM(*) D 2726, "Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimens".

   b. Marshall test parameters were obtained following the procedures delineated in the standard test ASTM D 1559 "Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus". The Marshall stability (lb) and the Marshall flow (0.01 in) were obtained for each layer.

   c. The asphalt content and the gradation of the recovered aggregate was obtained after the core-layer was subjected to the standard test ASTM D 2172 "Quantitative Extraction of Bitumen from Bituminous Paving Mixtures". The sieve analysis of the extracted aggregate was performed following specifications on ASTM C 136, "Sieve Analysis of Fine and Coarse Aggregates".

   d. The recovery of the extracted asphalt was obtained from the test procedures specified in ASTM D 1856 "Recovery of Asphalt from Solution by Abson Method".

   e. The penetration and viscosities of the weathered binders from each layer, were determined following the respective standard procedures: ASTM D 5, "Penetration of Bituminous Materials", and ASTM D 2170, "Kinematic Viscosity of Asphalts (Bitumens)".

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* ASTM Standard Test Procedures: "1984 Annual Book of ASTM Standards, Section 4, Vol. 04.03 [74].

3.3 - Statistical Analysis Variables

The response variables selected to perform a complete statistical analysis of the data obtained following the previously mentioned standard test procedures, are described next. There were six response variables selected among all the parameters measured for each core-layer based on the ability of these variables to characterize the weathered and in-place material that forms the county roads and city streets analyzed.

(1) The asphalt content (a) of each separate core-layer from a county road or city street's pavement. A total of 227 asphalt contents were determined.

(2) Asphalt penetration (p) and, (3) Kinematic viscosity (v). A total of 159 values of each parameter for the recovered original binders were recorded.

(4) The aggregate gradation modulus (gm), a measure of the surface area of the extracted aggregate, was used to analyze the existing variability in the original aggregate gradation. The review of the literature [58, 59, 60] revealed that the coarseness of an aggregate gradation can be expressed by a single number reflecting the amount of material passing the ten standard sieves from 1.1/2 inch through the No. 200 sieve. This number is the aggregate gradation modulus ($\bar{A}$), a parameter sufficiently sensitive to reflect changing requirements for mix proportions or asphalt content requirements as the aggregate grading

varies. Since there were 227 sieve analysis performed on the extracted aggregate, the same number of observations were obtained for the aggregate gradation modulus.

(5) The Marshall stiffness (ms) of the existing asphalt pavement mixture, was obtained by dividing the Marshall stability (lb) by the Marshall flow (0.01 inch) of each core-layer. The Marshall test procedure was used to attain these parameters. The Marshall stiffness (in lb/in) has been used in previous studies to evaluate asphalt pavement mixtures properties [8, 61]. This parameter was believed to better characterize the stability-flow properties of the existing pavement layers than if the stability and/or flow were considered as two separate test response variables. A total number of 178 Marshall stiffness values were obtained in this part of the study.

(6) As the last dependent variable, the thickness (t) of each pavement layer was measured and recorded. This variable was considered to be of some significance in this study since it is an approximation of the quantity of asphaltic concrete material that can be milled off the existing pavement. A total of 228 layer thicknesses (in inches) were recorded.

There were a total of six <u>independent variables</u> or factors in this study. These variables are listed in Table 3.2. A more detailed discussion on these factors can be found in Reference No. 104.

TABLE 3.2.- INDEPENDENT VARIABLES (ANOVA TEST)

Name	ANOVA Symbol	Total Pop´n.	Description
Climatic region	C	3	C=1: Northern Indiana C=2: Central Indiana C=3: Southern Indiana
Traffic type	TR	2	TR=1: Rural TR=2: Urban
Zones surveyed	Z	14	Z=1 to Z=8: Counties Z=9 to Z=14: Cities
Roads sampled	R	58	34 county roads 24 city streets
Samples obtained (pavement cores)	S	117	74 (counties) 43 (cities)
No. of layers	L	227	144 (counties) 83 (cities)

3.4 - Statistical Analysis Results

An extensive study of the materials variability found in Indiana's county roads and city streets was conducted by means of the analysis of variance (ANOVA) of the data obtained from the various asphalt pavements considered. The properties evaluated in this research work are thoroughly discussed in Reference No. 104, together with a summary of the ANOVA tests numerical results. The interested reader is referred to this particular document: "Materials Characterization and Economic Considerations of Cold-Mix Recycled Asphalt Pavements", Ph.D. Thesis, Purdue University, School of Civil Engineering, West Lafayette, IN, December 1985. Conclusions and recommendations based on the findings of the statistical analyses are presented here.

Asphalt Content of the Reclaimed Material.- It was found that the average asphalt contents of county road and city street pavements do not vary significantly. The statistical analysis of the data on this parameter showed also that there were no significant differences for all the roads within a particular county or city; nor were there differences in the asphalt content of all the road sections when considered together as a single factor in the analysis. There were no significant differences within a particular road section analyzed; i.e., it was found that on average, a county road or city street asphalt pavement can be considered to have an asphalt content equal to the average result of a minimum of four asphalt extraction results.

All this means that county road and city street asphalt pavements throughout Indiana can be considered as having similar variations in average asphalt contents. The same considerations can be given then, to this parameter, in the mix design of either rural or urban cold recycling asphalt mixtures throughout the State.

The main differences in asphalt contents were found among the various layers that constituted the pavements under study. In general, the asphalt content of the upper layer (surface or wearing course), was found to be +/- 1.0% higher than that of the lower layers. The lower layers' asphalt content vary within +/- 0.8% (refer to Table 3.3).

The other main conclusion drawn from the statistical analysis of the data is, that the asphalt content within a road section varies significantly from layer to layer vertically and not necessarily within the section, horizontally across the pavement. Each layer of pavement should then be milled off separately, and each layer's salvaged material should be stored or used individually if the variations in asphalt content among layers is found to be larger than +/- 1.0%. The depth of cutting, planing or milling becomes an important factor in obtaining a reclaimed material with small variations in asphalt content. Determinations of the pavement layers' thickness should be made as accurately as possible.

TABLE 3.3.- MEAN VALUES FOR ALL PAVEMENT LAYERS

Variables		Layer (L) 1	2	3	4
Asp.Cont. (%)	mean:	5.98	4.90	5.05	4.87
	n :	117	84	23	3
Asp. Pen. (0.1 mm)	mean:	42	40	48	29
	n :	78	59	20	2
Kin. Visc. (cSt)	mean:	679.4	750.6	677.0	1137.5
	n :	78	59	20	2
Grad. Mod. (A)	mean:	6.36	6.10	6.29	6.37
	n :	117	84	23	3
Mar. Stiff. (lb/in x10)	mean:	445.51	329.08	352.75	366.05
	n:	93	65	18	2
Thickness (in)	mean:	1.33	1.87	1.68	2.08
	n :	106	79	20	3

Note: n = number of observations/pavement layer

Penetration and Viscosity of the Original Binder.- These two parameters measure the extent to which oxidation and other chemical and weather-related factors have altered the ductility and flexibility of the original asphalt binder. These changes usually result in high viscosity values and low penetrations of the recovered asphalt. The outcome is an asphalt pavement with various degrees and types of distresses. Penetration and viscosity values were found to be significantly different from one road pavement to another, and within a particular road or street section, from layer to layer. From the observations of the ANOVA results one can conclude that there were no practical differences among the 8 zones analyzed.

Other findings were that although these two parameters are weather related, the effects of the various climatological regions found in the State of Indiana were minimal or non-existent. Asphalt residues' penetrations or viscosities, whether from county roads, or city streets' pavements, can be considered as becoming brittle or oxidizing in a similar manner. Finally, the variations in the hardness of the original asphalt within a recycling project's size (road section to be rehabilitated), seem to be minimal and of small practical importance. However, the variations between layers from pavement to pavement were found to be significant. This means that for a particular asphalt pavement, the various constituting layers can be scarified, ripped and/or cut and mixed together, and can be considered as having an average asphalt penetration value throughout the entire recycled section for mix design purposes. These findings are important for the proper design of the recycled mix. Rejuvenating, softening, modifying or recycling agents are generally used to restore the ductility and the original properties of the original asphalt. The optimum quantities and type of recycling agent will depend to a large extent on the hardness of this asphalt residue. It can be stated then, that the same mix design can be used in a recycling project if the salvaged material within a particular pavement section comes from layers with similar asphalt penetration and/or viscosity. Careful determination of these two parameters should be made and the same type and proportions of recycling agent can only be used for a particular road section for which they were determined.

Gradation of the Extracted Aggregate.- Aggregates recovered from existing pavements were found not to differ significantly in gradation. Aggregate gradations from the county roads and city streets' asphalt pavements analyzed were found to be very similar: within a narrow gradation band (see Figure 3.3), and within range of standard virgin quality material (Figure 3.4).

These aggregates were found to differ only between layers of the various road sections considered in this study. A close analysis of the aggregate gradation moduli of these aggregates (see Table 3.3), shows that the differences obtained between average values is not large enough to be of any practical significance. This means that the average gradation of the various layers that are being considered for recycling, in a particular project, can be used for mix design purposes. These average

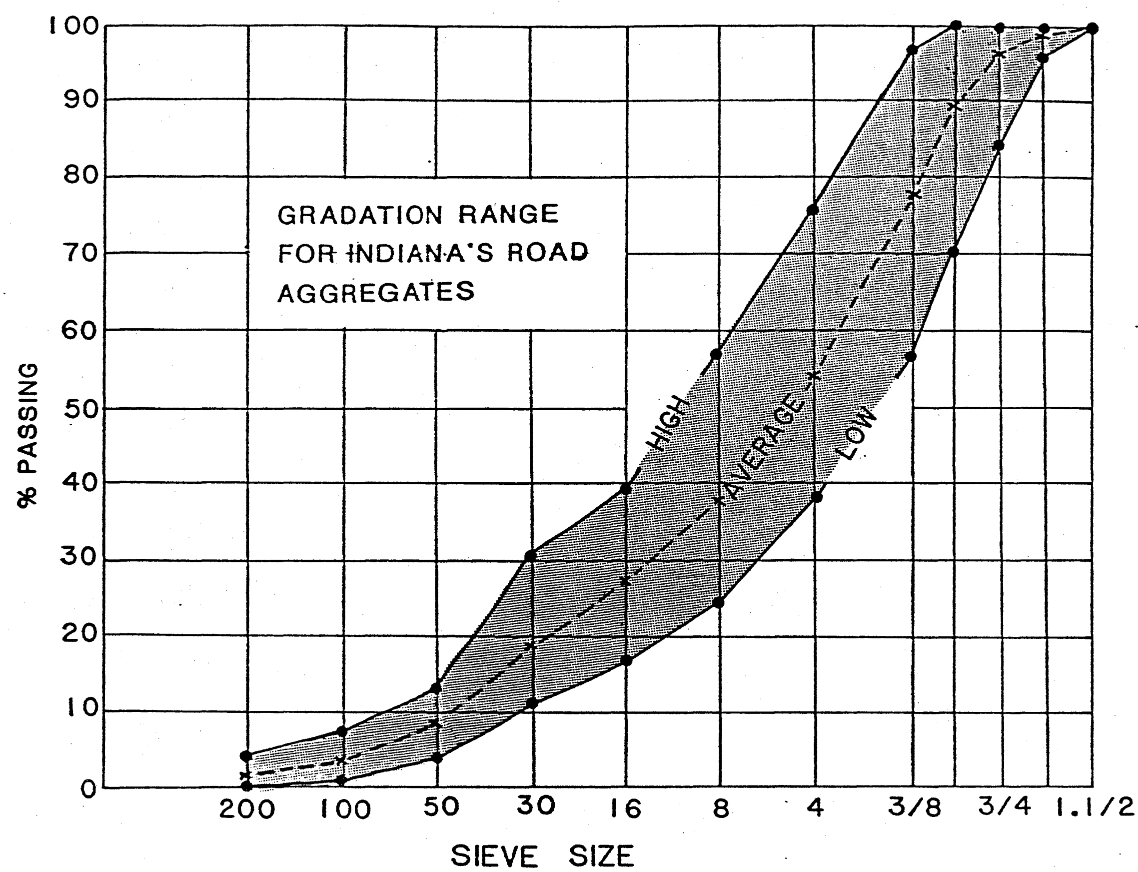


FIGURE 3.3 .- EXTRACTED AGGREGATE GRADATION BAND - INDIANA'S PAVEMENTS

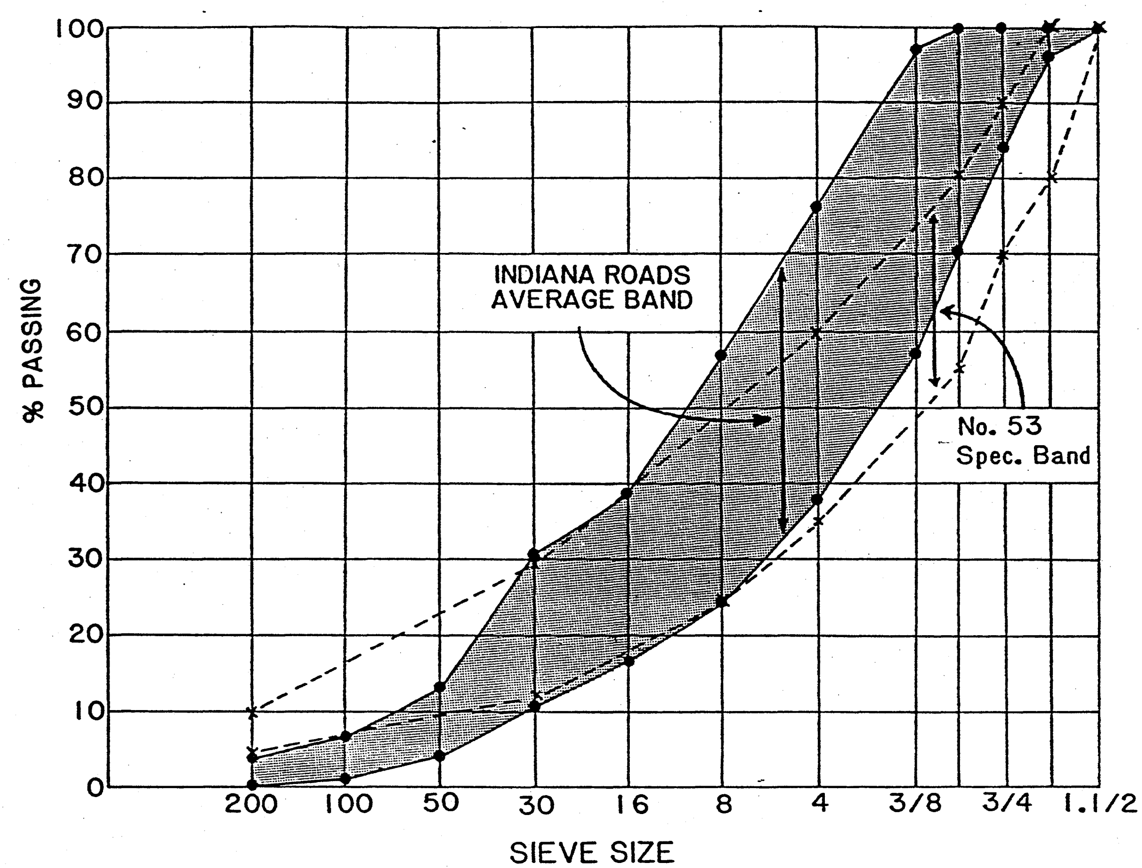


FIGURE 3. 4 .- AVERAGE BAND AND STANDARD GRADATION

gradation values would inform the design engineer of the required sizes and proportions of virgin aggregate that the reclaimed pavement material needs to meet a particular standard gradation for base, subbase or surface course mix.

The aggregate gradation modulus measures to some extent the necessary amounts of binder that a particular aggregate may require to perform well as a paving mix under varying traffic load and weather effects (refer to Section 3.3 for a detailed explanation of the gradation modulus of an aggregate).

Marshall Stiffness of the Asphalt Pavement Layers.- This parameter measures the relative stability and strength of an asphalt pavement mixture. This in turn relates somehow to properties of the materials that form a particular mix being analyzed. The soundness, strength and size distribution of the aggregate (interlocking characteristics) will influence the stability and stiffness of the mix. The properties of the binder will also be reflected in this parameter. Hard, stripped asphalt with no binding properties, as well as soft and oily asphalt will give weak and unstable mixes.

The statistical analysis of the Marshall stiffness data obtained from core-layers of Indiana county roads and city streets' asphalt pavements led to the following conclusions:

The stability of the mixes that form the various pavement layers were statistically different from each other, with the top layer being the stiffest of them all in most cases (see Table 3.3). This is due to the fact that newer, less deteriorated and, therefore, stronger mixes form the wearing surface of most pavements in service.

The difference in average Marshall stiffness between the various zones of the study was also found to be significant; but a close analysis of the ANOVA test results shows that the mean squares (MS) of the data for the layers factor (L) is by far the largest of the MS values. The zones (Z) factor and the interaction term L*Z are almost not statistically significant. These observations and the small sample size for some of the zones in the study led one to believe that the only practical differences among pavement stiffness occurs among the layers that form the pavement being analyzed.

The practical significance of these findings is that if a recycling project is undertaken with the sole objective of restoring the surface or top few inches of a deteriorated asphalt pavement (surface recycling, for example), care must be taken in determining the strength and stability of the underlying materials. If new recycled asphalt mix is placed on top of weak and unstable pavement layers, most likely the structural support will be such that the old distresses and faults that made the pavement a candidate for rehabilitation in the first place, will be evident again in a very short time.

For a detailed description and more information on cold recycling methods that improve the structural capacity and increased service life of asphalt pavements, the reader is referred to Chapter 2, Section 2.1, and Tables 1.1 and 1.2 of this report.

Pavement Layer Thickness.- This parameter was analyzed in order to help characterize the variability among pavements in Indiana's secondary roads system. It is a parameter of little practical significance for recycled mixtures mix design purposes; however, it helps in a way to measure the relative quantities of existing materials that are available for recycling.

The statistical analysis of these data indicates that pavement layer thicknesses were significantly different between the layers of a particular roadway pavement and between the layers of pavements from the various counties and cities investigated in this research work. More material (thicker layers) can be found, on the average, in lower layers of the pavement as compared with upper layers. This is due to the fact that lower layers are, in most cases, thicker base course asphalt pavement layers, and the upper layers are formed of relatively thin surface treatments or asphalt overlays. Routine maintenance practices commonly adopted by county and local highway agencies consist mainly of chip seal and/or single surface treatments with limited service life and almost no structural support added to the pavement.

3.5 - Parameters Measured: Range of Values

This section in the analysis of field pavement cores, presents the range of values obtained from pavement core-layers subjected to the test procedures listed in Section 3.2 of this chapter. This information is presented as a complement to the data already analyzed for better illustrating the variability and composition of Indiana's County and City asphalt pavements.

A series of graphs depict the various range of values obtained for variables of interest such as gradation of the extracted aggregate, asphalt content for each pavement layer, etc.

Figure 3.3 presents the gradation band obtained from the sieve analyses results of 227 extracted aggregate samples. Figure 3.4 depicts these results as they compare with a standard gradation such as Indiana's IDOH No. 53 aggregate. It can be seen from these graphs that the extracted aggregates analyzed were lacking of fine particles. This is contrary to the common belief that aggregates under several years of service suffer traffic and weather disintegration and crushing, which in turn generates fines. It can also be seen that even though the aggregates have in general a good particle size distribution, they have less than desirable amounts of materials passing No. 50, 100 and 200 sieves.

Figure 3.5 presents the information listed in Table 3.3 together with the minimum and maximum values recorded for each parameter measured. Even though the average values obtained for the top two pavement layers were generally close to each other, the range of values for each layer varied considerably.

Figure 3.6 shows that the average values obtained for the parameters measured in county roads and city streets samples are quite similar; however, the range of the maximums and minimums observed was substantially large and different from each other.

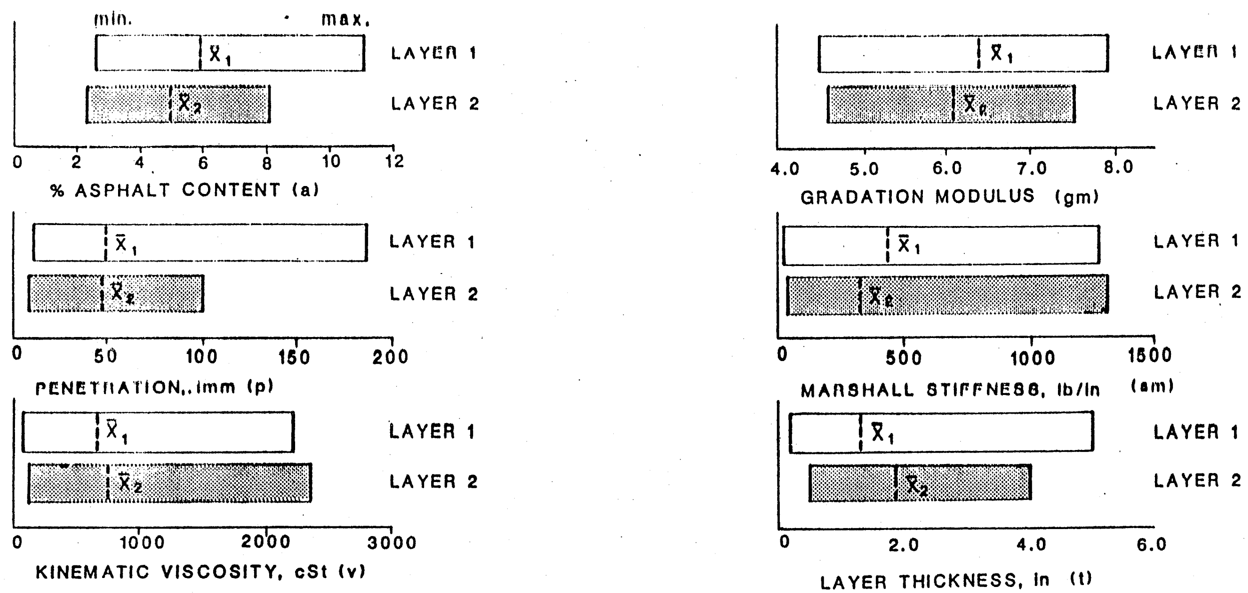


FIGURE 3.5 .- AVERAGE AND RANGE OF VALUES FOR VARIOUS PARAMETERS

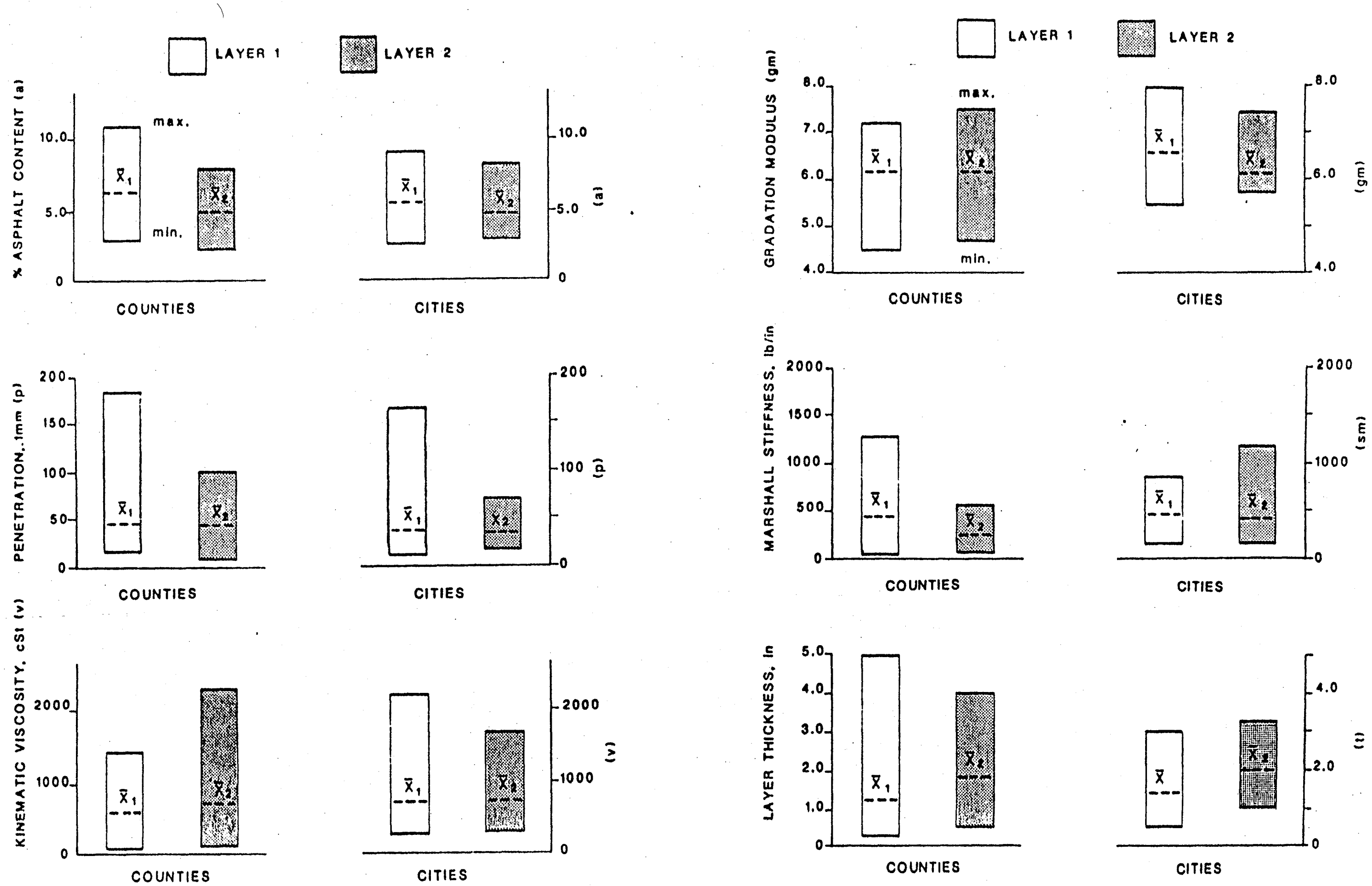


FIGURE 3.6.- RANGE OF PARAMETERS FOR COUNTIES AND CITIES PAVEMENTS

Finally, the various results obtained from asphalt pavement samples located in the three geographical regions of Indiana are presented in Figure 3.7. This plot shows consistently that the top layer and the subsequent one have very similar penetration and viscosity average values.

This, together with the findings discussed in previous sections, indicates that there are no substantial differences in the weather effects throughout the State. The stability and gradation of the pavements from these three regions appear to be also within close range of each other. However, layer two shows less asphalt content than the top pavement layer (between 0.50 and 1.20%); and layer two appears to be twice as thick as the top layer analyzed.

3.6 - Summary

As a summary, the following observations are considered pertinent as to how the asphalt pavement material to be recycled might affect the final recycled mix:

Based on the previous observations and discussions, samples obtained from asphalt pavements in Indiana prior to milling, ripping, breaking, or other processing, are likely to exhibit highly variable results from penetration and viscosity of the original asphalt binder to the stiffness of the existing asphalt mix. This appears to result from local effects, probably associated with the type and amount of distress. Although Kallas [33] reported that there is a relationship between asphalt hardening

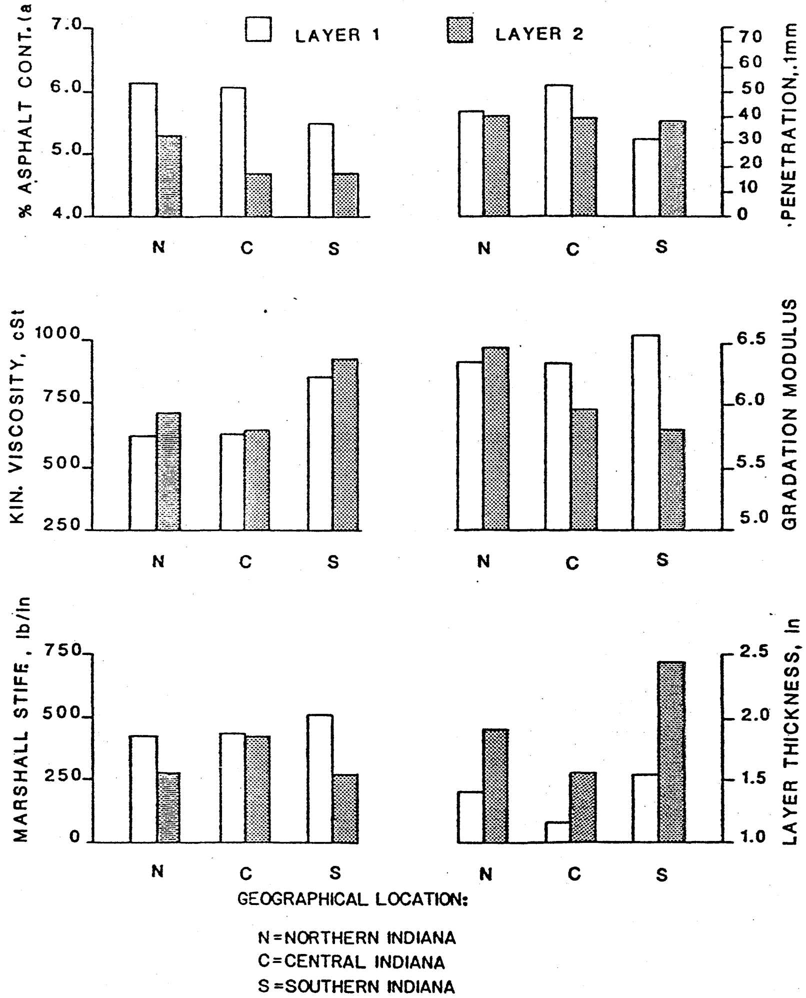


FIGURE 3.7 .- RANGE OF PARAMETERS MEASURED FOR VARIOUS GEOGRAPHICAL LOCATIONS

and cracking, there was no attempt made to document such an observation on this project, and therefore, those conclusions cannot be substantiated from this project's data.

Inspection of the data indicated that variations in penetration and viscosity test results on recovered asphalts were randomly located throughout the asphalt pavements studied. These observations, and consideration of the large standard deviations associated with these test data, indicates that quite a large number of test locations would be required to discover the extent of pavement having different test properties. In most cases, the amount of testing required would be more extensive than most agencies would consider feasible and would only be of practical use if the more extensive testing program resulted in different mix designs for each section of the project having different test properties.

In general it may be concluded that county roads and city streets' asphalt pavements in Indiana that are candidates for recycling can be expected to have a comparatively high level of variability. Some improvement may be obtained during the processing from pavement to reclaimed material through a milling operation, or by separating the project into sub-units that might have different mix designs, for example.

It is recommended that the following procedure be used when sampling asphalt concrete from the roadway prior to milling or another process used for salvaging it:

a.) Obtain samples and perform laboratory tests as outlined in Sections 3.1 and 3.2 of this report.

b.) Establish construction units only on the basis of aggregate gradation and percent asphalt, unless it can clearly be demonstrated that penetration or viscosity test properties are quite different.

c.) Determine layer thickness and layer structural properties by means of cores testing in the laboratory.

d.) Perform a detailed mix design study for each individual recycling project being undertaken. It is also recommended, that where possible, final mix designs be based on reclaimed and processed asphalt pavement material.

e.) Approach every recycling job with as much planning, design, and expertise as practically feasible. The variability of the materials that form Indiana's county roads and city streets was demonstrated by this study to be such that even conventional new-material construction practices, adopted in a generalized and broad way, may lead to short-term and limited improvement of the pavements being rehabilitated.

CHAPTER 4

LABORATORY STUDIES OF THE EFFECT OF VARIOUS FACTORS ON THE BEHAVIOR OF RECYCLED ASPHALT MIXES

This chapter describes the various laboratory studies performed in conjunction with the analyses of asphalt pavement The testing of field cores and laboratory specimens was conducted in order to better characterize the recycled pavement materials that can be obtained from existing Indiana county roads and city streets.

The materials and laboratory test procedures discussed here were selected primarily based on the range of values obtained previously for extracted aggregate gradations and weathered binder parameters. The test procedures used to investigate the behavior of the laboratory recycled mixtures were widely reported throughout the related literature [8, 28, 39, 49, 50, 51, 52, 53, 67, 68, 69, 70, 84, 85, 86].

The characteristics of the materials used in this laboratory analysis closely resemble the characteristics of the materials described in the previous chapter of this report. The test procedures adopted were considered to be the most appropriate techniques that can be used to characterize cold-mix recycled asphalt mixtures in this study. With these considerations in mind, laboratory specimens that closely resemble cold recycled pavement mixtures were prepared and tested in the laboratory.

4.1 - Materials and Equipment

The materials used to prepare cold-mix recycled specimens are described in this section of the report. A detailed description of the equipment used for testing these specimens can be found in Reference No. 104.

4.1.1 Reclaimed Asphalt Pavement Material

The reclaimed asphalt pavement (RAP) material used in this study was obtained from stockpiles located in the city of Lafayette, Indiana. After preliminary examination of asphalt properties and extracted aggregate gradations, four different stockpiles were selected to obtain the RAP material to be used in this laboratory work. The source of these RAPs were existing city streets, namely, Union Street, Kossuth Street, Sixth Street and Ferry Street.

The material was milled from existing weathered asphalt pavements of varying composition and characteristics. The maximum size of all the extracted aggregates was 1.0 inch, as can be seen in Figure 4.1. This graph presents the average gradation obtained for all the extracted aggregates of RAP samples, as they compare with the average gradation band obtained for Indiana's county roads and city streets extracted aggregates. The percent material

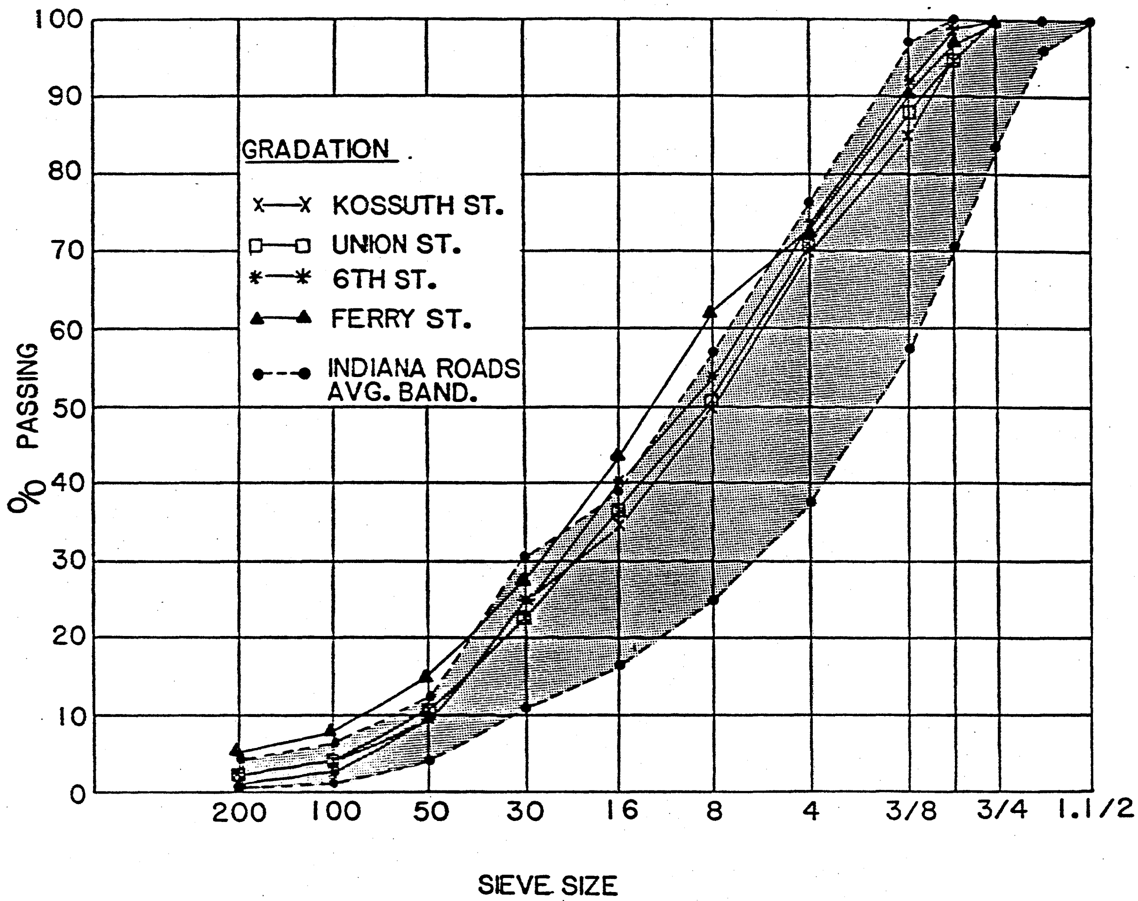


FIGURE 4.1.- RAPs AND GRAND AVERAGE GRADATIONS

passing the various sieve sizes (for the RAP samples), lies close to the upper band of the field cores' extracted gradation range.

The properties of these RAPs are presented in Tables 4.1 and 4.2. The properties of their respective recovered aged asphalt residues are presented in Table 4.1. The range of values reported in this table are the results of 4 to 9 representative samples tested for each RAP material. Figure 4.2 and Table 4.2 show the results of the sieve analyses performed on the extracted aggregate of the four RAP materials. These RAP materials were taken to the laboratory, dried at 140 deg.F for 1 hour (to eliminate field moisture), and stored for later use. All specimens prepared for this laboratory work were made using one of these recycled materials in combination with varying amounts of recycling agents. The agents used to prepare laboratory samples are described in the next subsection.

4.1.2 Recycling Agents

The recycling agents used in preparing the laboratory specimens were selected based on their availability and common use in cold-mix paving operations throughout the State of Indiana. In total, six liquid agents were used. Their properties are listed in Tables 4.3 to 4.8. Three were common high float asphalt emulsions used in cold-mix bituminous mixtures. The other three agents were rejuvenating agents widely used in cold-mix recycling jobs throughout the country [8, 12, 13, 15, 36, 42, 51, 54, 67, 69, 70, 71, 72, 73, 84].

TABLE 4.1.- PROPERTIES OF RECOVERED AGED ASPHALT RESIDUES

	Recycled Asphalt Pavement (RAP) Source			
Property	Kossuth St.	Union St.	6th. St.	Ferry St.
Asphalt Content(1), %	5.0 (± .25) %	5.5 (± .5) %	6.5 (± .3) %	5.9 (± .5) %
Penetration(2), .1 mm	13 (± 1)	20 (± 5)	14 (±1)	30 (± 5)
Kin. Viscosity(3), cSt.	1575 (± 25)	1500 (± 500)	1675 (± 150)	800 (± 100)
Abs. Viscosity(4), p.	87540 (± 5000)	65000 (± 5000)	75000 (± 2000)	13500 (± 500)
No. Samples Tested	4	6	4	9

Note: (1) ASTM D-2172 [74]
(2) ASTM D-5 [74]
(3) ASTM D-2170 [74]
(4) ASTM D-2171 [74]

TABLE 4.2.- SIEVE ANALYSIS OF RAP AND RECOVERED AGGREGATE (% passing)

	Recycled Asphalt Pavement (RAP) Source							
	Kossuth St.		Union St.		6th St.		Ferry St.	
Sieve Size	RAP	Recov.	RAP	Recov.	RAP	Recov.	RAP	Recov.
1 in.	100.	100.	100.	100.	100.	100.	100.	100.
3/4	98.	100.	95.	100.	97.	100.	92.	100.
1/2	90.	95.	83.	95.	91.	99.	81.	98.
3/8	80.	85.	73.	88.	80.	92.	67.	91.
No. 4	55.	70.	48.	71.	47.	73.	39.	73.
8	30.	50.	29.	51.	28.	54.	21.5	62.
16	20.	35.	14.	37.	12.	40.	8.	44.
30	8.	25.	5.5	23.	3.	25.	2.	28.
50	3.	10.	2.	10.5	0.8	10.	0.5	15.
100	1.	5.	0.5	5.	0.5	4.	0.1	8.
200	0.5	2.5	0.2	2.5	0.3	0.7	0.	5.

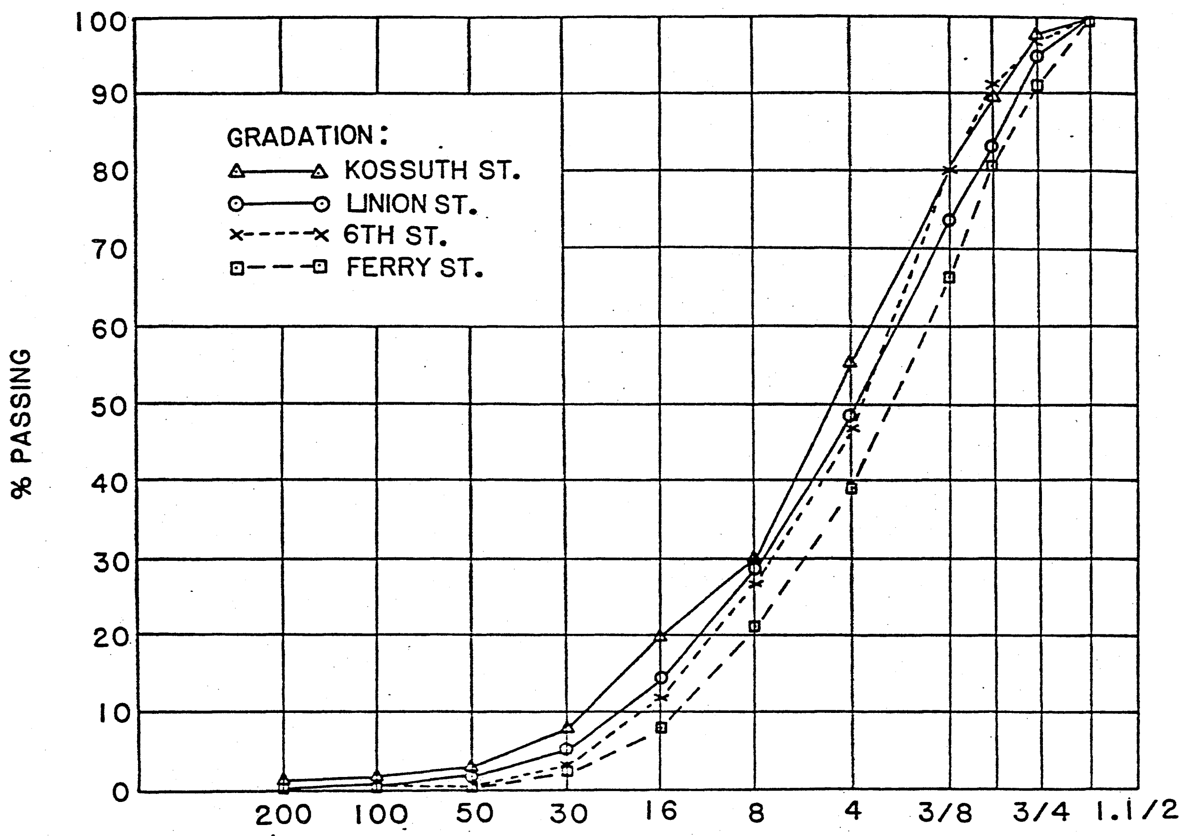


FIGURE 4.2.- STOCKPILED RAPs GRADATION

All of the virgin recycling agents used in this study have properties within specified standard limits. An analysis of the results presented in Tables 4.3, 4.4 and 4.5, shows that the asphalt emulsions met the requirements set by the "1985 - Indiana Department of Highways - Standard Specifications". The various material's property limits supplied by the manufacturer of the rejuvenating agents were confirmed by the test procedures listed in Tables 4.6, 4.7 and 4.8.

4.1.3 Laboratory Equipment and Test Procedures

This section gives a list of the major pieces of equipment that were used in preparing and testing specimens for this laboratory work.

- Gyratory Testing Machine (ASTM D 3387)
- Marshall Stability Machine (ASTM D 1559)
- Diametral Resilient Modulus Machine (ASTM D 4123)
- Pulse Velocity Sonic Wave Machine (ASTM D 2845)

The specimen preparation and the experimental procedures used throughout this study were in most cases following well accepted practices and standards [45, 52, 59, 61, 74]. The interested reader is referred to Reference No. 104 for a detailed description of test equipment and procedures used to obtain the results discussed next.

TABLE 4.3.- PROPERTIES OF ASPHALT EMULSION AE-90

ASTM Standard Tests (*)	IDOH 1985 Spec's.	Test Results
Residue from Res. by Distillation	68 min	72
Oil Portion, ml. oil/100 gr.	4. max	0
Float Test, 140°F, sec.	1200 min	>>1200
Penetration, 100 gr., 77°F, 5 sec. 50 gr., 77°F, 5 sec.	100-200 -	105 -
Absolute Viscosity, 140°F, 300 mm Hg vac., poise	-	1270
Kinematic Viscosity, 275°F, cSt.	-	4465

* 1984 Annual Book of ASTM Standards, Section 4, Vol. 04.03

TABLE 4.4.- PROPERTIES OF ASPHALT EMULSION AE-150

ASTM Standard Tests (*)	IDOH 1985 Spec's.	Test Results
Residue from Res. by Distillation	68 min	73.5
Oil Portion, ml. oil/100 gr.	7.0 max	2.5
Float Test, 140°F, sec.	1200 min	>>1200
Penetration, 100 gr., 77°F, 5 sec. 50 gr., 77°F, 5 sec.	- 100-300	- 221
Absolute Viscosity, 140°F, 300 mm Hg vac., poise	-	1070
Kinematic Viscosity, 275°F, cSt.	-	9615

* 1984 Annual Book of ASTM Standards, Section 4, Vol. 04.03

TABLE 4.5.- PROPERTIES OF ASPHALT EMULSION AE-300

ASTM Standard Tests (*)	IDOH 1985 Spec's.	Test Results
Residue from Res. by Distillation	65 min	69
Oil Portion, ml. oil/100 gr.	7 max	5
Float Test, 140°F, sec.	1200 min	>1200
Penetration, 100 gr., 77°F, 5 sec. 50 gr., 77°F, 5 sec.	- 300 min	- >300
Absolute Viscosity, 140°F, 300 mm Hg vac., poise	-	255
Kinematic Viscosity, 275°F, cSt.	-	6110

* 1984 Annual Book of ASTM Standards, Section 4, Vol. 04.03

TABLE 4.6.- PROPERTIES OF REJUVENATING AGENT CYCLOGENE-ME

ASTM Standard Tests (*)	Manufacturer Information	Test Results
Residue from Res. by Distillation	62 min	66.3
Oil Portion, ml. oil/100 gr.	- max	0
Float Test, 140°F, sec.	- min	-
Penetration, 100 gr., 77°F, 5 sec. 50 gr., 77°F, 5 sec.	- -	- >300
Absolute Viscosity, 140°F, 300 mm Hg vac., poise	-	22
Kinematic Viscosity, 140°F, cSt.	1000-4000	2240
Kinematic Viscosity, 275°F, cSt.	-	43.5
Specific Gravity, Residue	0.98-1.02	1.01

* 1984 Annual Book of ASTM Standards, Section 4, Vol. 04.03

TABLE 4.7.- PROPERTIES OF REJUVENATING AGENT RECLAMITE

ASTM Standard Tests (*)	Manufacturer Information	Test Results
Residue from Res. by Distillation	60-65 min	64.3
Oil Portion, ml. oil/100 gr.	- max	0.25
Float Test, 140°F, sec.	- min	-
Penetration, 100 gr., 77°F, 5 sec. 50 gr., 77°F, 5 sec.	- -	- <<300
Absolute Viscosity, 140°F, 300 mm Hg vac., poise	-	1.77
Kinematic Viscosity, 140°F, cSt.	100-200	180
Kinematic Viscosity, 275°F, cSt.	-	10.5

* 1984 Annual Book of ASTM Standards, Section 4, Vol. 04.03

TABLE 4.8.- PROPERTIES OF REJUVENATING AGENT HFRA

ASTM Standard Tests (*)	Manufacturer Information	Test Results
Residue from Res. by Distillation	66.7 min	67
Oil Portion, ml. oil/100 gr.	- max	0.5
Float Test, 140°F, sec.	- min	>1200
Penetration, 100 gr., 77°F, 5 sec. 50 gr., 77°F, 5 sec.	- -	- -
Absolute Viscosity, 140°F, 300 mm Hg vac., poise	-	-
Kinematic Viscosity, 275°F, cSt.	-	395

* 1984 Annual Book of ASTM Standards, Section 4, Vol. 04.03

4.2 - Effect of Mixing Water, Binder Content, Pre-Compaction Curing and Compactive Effort

This section describes the materials and procedures used in the characterization of the effects of the factors mentioned above, upon the behavior of recycled asphalt pavement mixtures prepared and tested in the laboratory.

Thorough mixing of the recycling agent and initial moisture added are important to obtain a strong and stable recycled mix. The use of some initial moisture helps the dispersion of the agent throughout the mix [8, 16, 21, 61, 75, 77]. However, the recycling agent or new binder, in order to properly bond together the RAP particles, must first displace the film of water on the surface of the RAP. It is then, only, when the "rejuvenating" or softening effect on the aged original binder starts taking effect.

Mixing Water.- The effects of mixing water were as follows:

(a) Trial mixes prepared at various initial moisture contents (with no recycling agent added) showed that at low levels of moisture the stability and density of the mix was quite low. These two parameters increased with additional moisture until they started to level-off. It was found though, that after adding approximately 2.0 to 3.0% moisture (by weight of dry RAP material), the gain in stability and density was very small.

(b) These findings, together with the results obtained from trial specimens using various AE-150 (asphalt emulsion) contents, demonstrated that a typical RAP material obtained from an Indiana county road or city street asphalt pavement gives a stronger and denser cold recycled mix at mixing water contents of less than 3.0% (Figures 4.3 and 4.4).

Virgin Binder Content.- The effects of new binder added to the reclaimed asphalt pavement (RAP) can be seen in Figures 4.3 to 4.8. These effects are summarized as follows:

(a) In all cases, the density of the samples increased with the increase in new binder (AE-150) added (Figures 4.3 and 4.7).

(b) The Marshall stability reached maximum values at much lower levels of new binder added than those required for maximum densities. In fact, levels of emulsion larger than 2.0% by weight of dry RAP made stabilities decrease considerably, independent of the RAP type or mixing water content (Figure 4.4, 4.5, 4.6 and 4.8).

(c) When other factors were involved, such as pre-compaction curing and compactive effort, the trends were the same as described before (Figures 4.5 to 4.8).

Pre-Compaction Curing.- In order to obtain the rejuvenating or softening effects from the recycling agents or modifiers used, aeration of the mix after mixing and prior to compaction, appears to be of some significance [8, 34, 73, 85]. This initial "curing" period of a few hours before compaction is important in field and laboratory cold-mix recycling operations.

Two different aeration periods were used in this laboratory study: (i) mixing of the materials needed for the sample, fol-

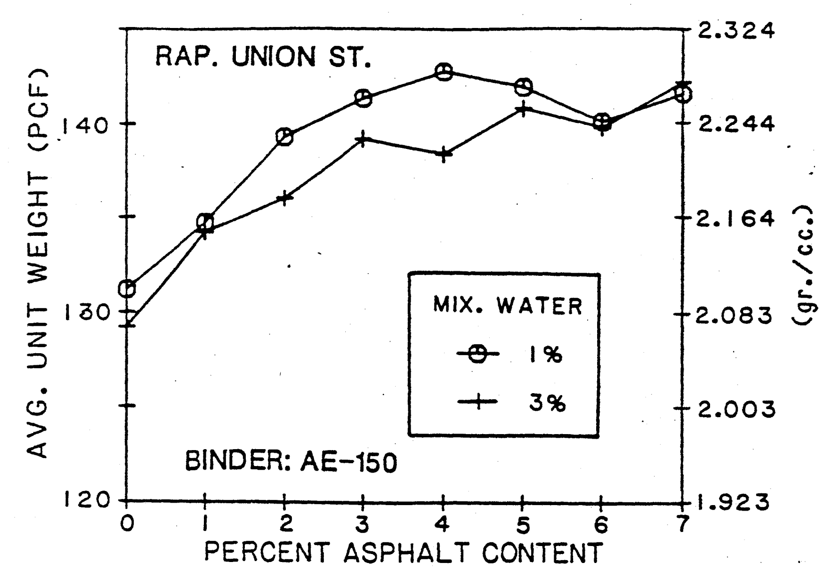


FIGURE 4. 3.- % BINDER VS. DENSITY (UNION ST.)

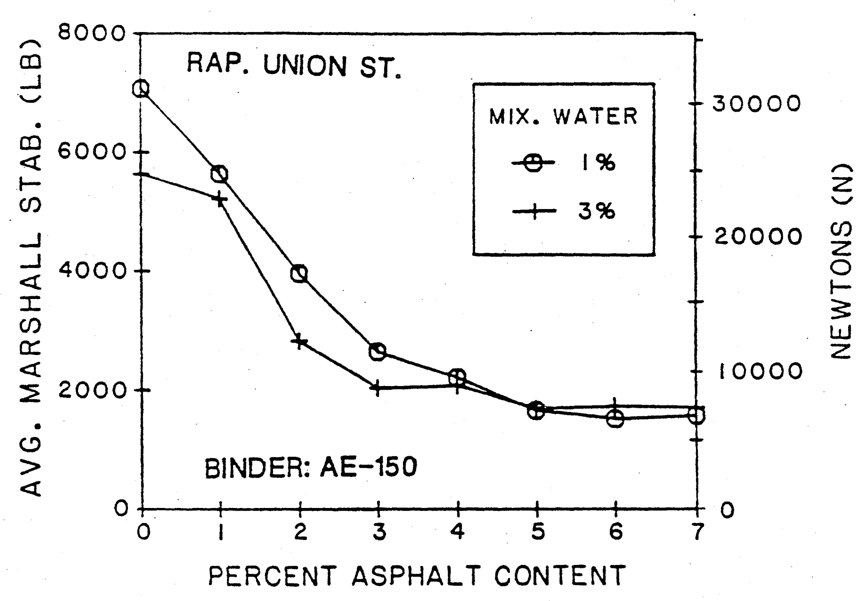


FIGURE 4. 4.- % BINDER VS. MARSHALL STABILITY (UNION ST.)

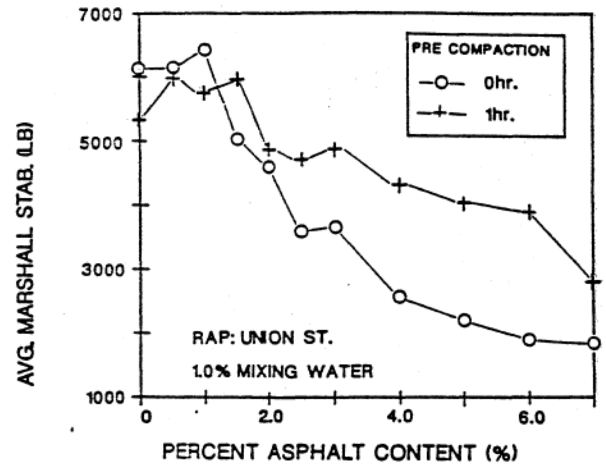


FIGURE 4.5 .- % BINDER VS. MARSHALL STABILITY (1.0 % MIXING WATER)

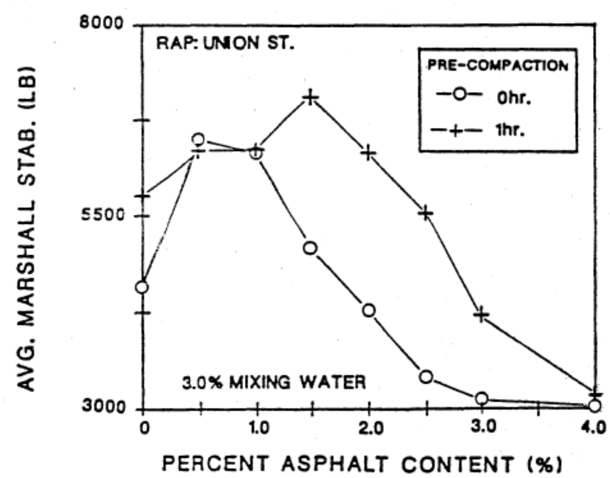


FIGURE 4.6 .- % BINDER VS. MARSHALL STABILITY (3.0 % MIXING WATER)

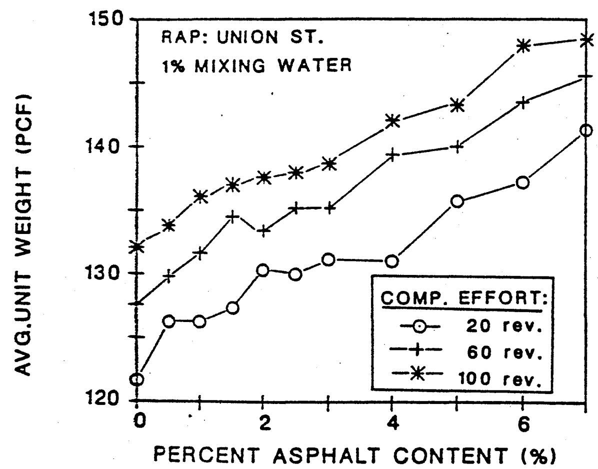


FIGURE 4. 7.- % BINDER VS. DENSITY (VARIOUS COMPACTIONS)

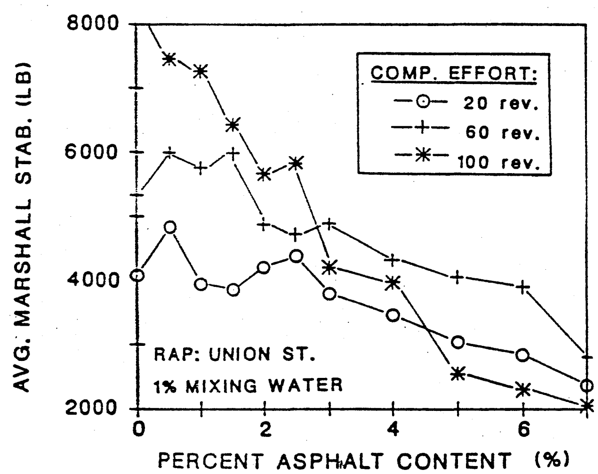


FIGURE 4. 8.- % BINDER VS. MARSHALL STABILITY
(COMPACTION: 20, 60 AND 100 REVOLUTIONS)

lowed immediately by compaction, and (ii) mixing followed by 1 hr. in a 140 deg.F oven, two hrs. or less for cooling to room temperature and then compaction. The findings from these experiments were that:

(a) In most cases, Marshall stabilities were higher for samples pre-cured for 1 hr.; densities, on the other hand, were found to be practically the same, concluding that pre-compaction curing has a minor effect on the density of the compacted recycled mix.

(b) Curing of the mix for one hour before compaction helped to eliminate almost half the moisture present in the mixture. The aeration of the mix then, plays an important role in allowing the recycled mix to rapidly gain early strength and stability since the asphalt residue of the emulsified agents used can only start the binding process with aggregate particles after demulsification occurs.

Aeration of the cold recycled mix is usually accomplished in the field by blade mixing [76]. The shifting of the RAP with recycling agent from one side of the roadway to the other (ensuring also the uniformity of the mixture), may be all the aeration that is necessary during periods of hot, dry weather. During cool weather periods it is sometimes necessary to shift the material for longer than 24 hours. Pre-compaction aeration effects on laboratory cold recycled mixes were also reported by Iida [77] and others [8, 34, 86].

Compactive Effort.- The findings using three different compactive efforts were as follows:

(a) Higher compactive efforts generally produced high densities of the mix (Figure 4.7).

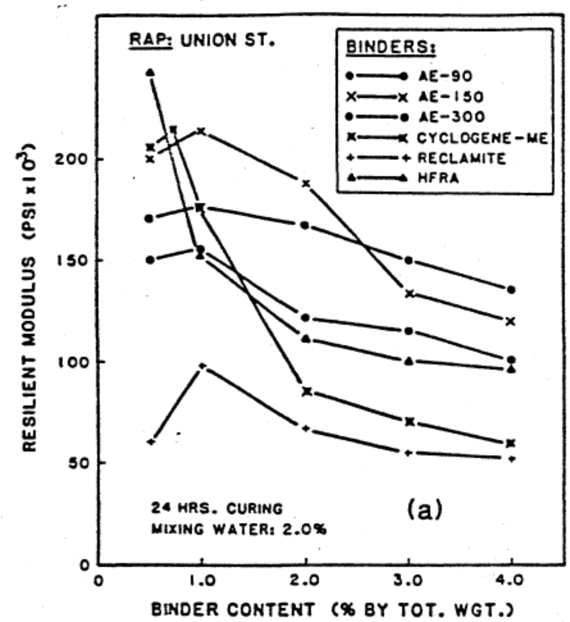
(b) High compactive efforts also increased the stability of the samples; however, when the binder content was higher than 2.5%, the mix turned unstable and the stabilities were low (Figure 4.8). The 60 revolutions and 200 psi. levels in the gyratory machine gave consistently high stability values throughout the entire range of new binder added; this compactive effort is also reported to produce compacted specimens that closely resemble field densities for this type of asphalt mixture [8].

4.3 - Effects of Recycling Agent Type and Curing Time

This section presents the test results obtained from cold-mix recycled specimens prepared using six different recycling agents and various periods of curing time.

Different Recycling Agents.- The various types of binders and recycling agents used in this laboratory study affected the performance of the cold recycled mix as follows:

(a) The level of recycling agent added had significant effect on the resilient modulus, Marshall stability, density and pulse velocity of the recycled mix. The resilience and stability of the mixtures decreased with the increase in agent added (Figures 4.9-a and 4.9-b), while the density and pulse velocity increased with more binder added (Figures 4.10-a and 4.10-b).



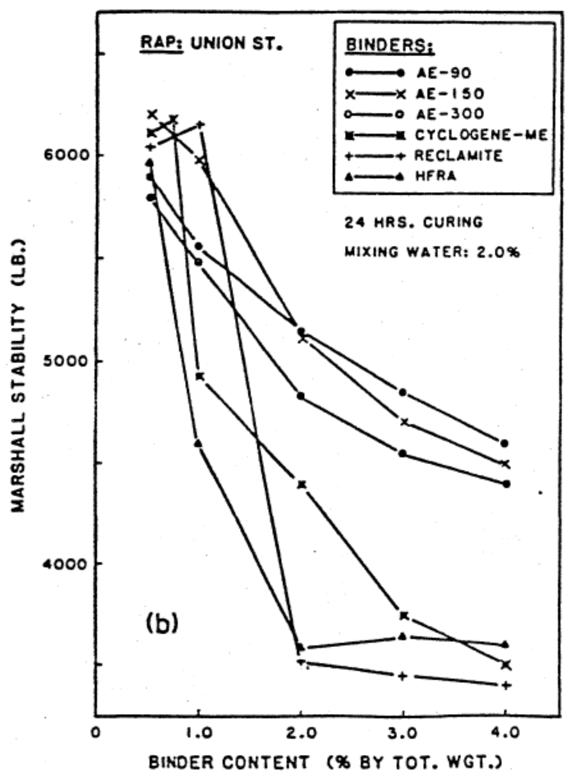


FIGURE 4.9 .- % BINDER VS. RESILIENT MODULUS (a) AND MARSHALL STABILITY (b)

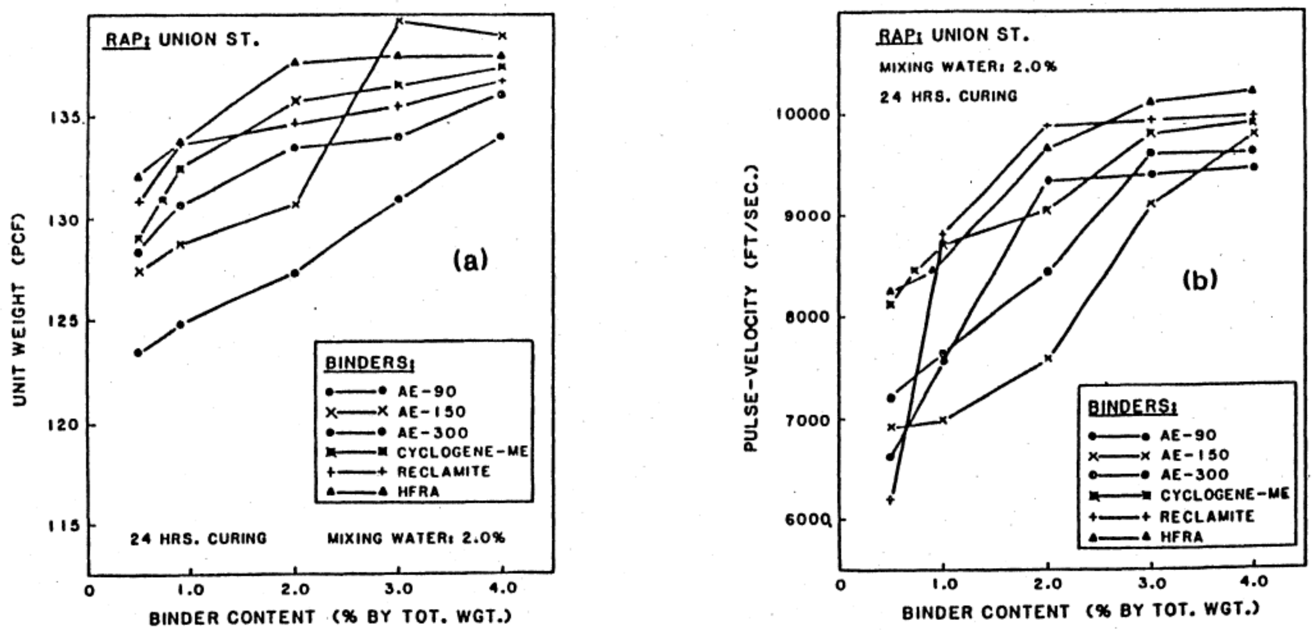


FIGURE 4.10.- % BINDER VS. DENSITY (a) AND PULSE VELOCITY (b)

(b) When the three asphalt emulsions (AE-90, AE-150 and AE-300), were used as the agent added, the resilient modulus and stability of the specimens were higher at binder contents equal or greater than 2.0% by weight of RAP, as compared with the values for samples prepared with the other three recycling agents. This trend was not so clear for agent levels below the 2.0% content. This tends to indicate that stability and resilient modulus of the cold recycled mix at low levels of agent content, were not consistently affected by the difference in viscosity and other properties of the residues that form the various agents and binders used.

(c) In most cases, density and pulse velocity of the mix were higher for the specimens prepared with the soft-residue agents (Cyclogene-ME, Reclamite and HFRA) than for those mixes prepared with harder asphalt residue agents.

(d) Recycling agents (at 2.0% level), with harder residues, yielded recovered asphalt contents within expected ranges. On the other hand, the recovered asphalt contents from recycled mixtures made with soft residue agents were off the expected range by about 1.0% in some cases.

(e) When the properties of the extracted asphalt were analyzed and compared with original binder properties of the RAPs used, a consistent trend was observed: (i) the penetrations of the recovered asphalt were all increased by adding 2.0% (by RAP weight) of recycling agent to the mix (Figure 4.11-a); and (ii) the Absolute viscosities (Figure 4.11-b), and the Kinematic viscosities (Figure 4.11-c), were all reduced when 2.0% of recycling

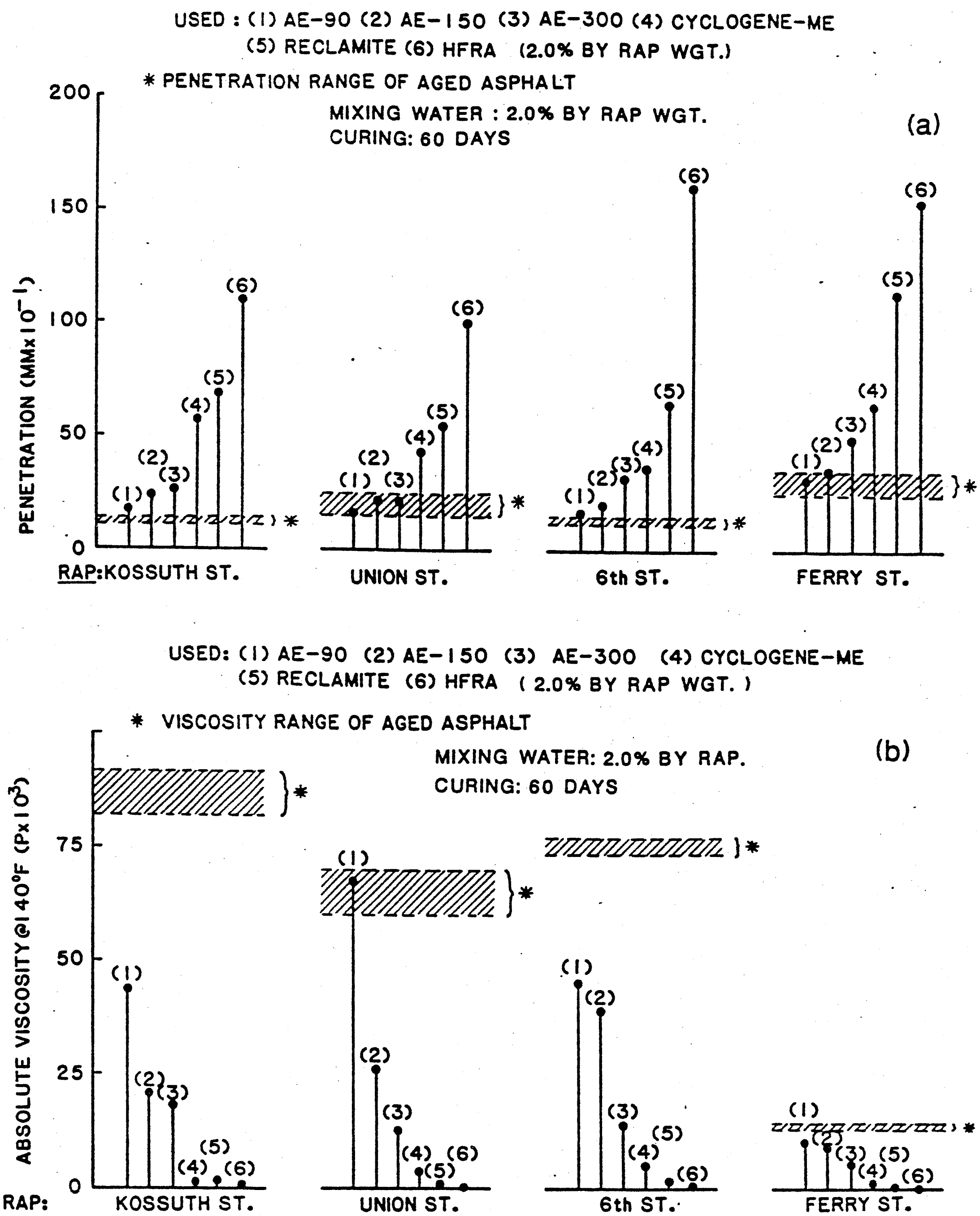


FIGURE 4.11.- EFFECTS OF VARIOUS RECYCLING AGENTS UPON PENETRATION (a), ABSOLUTE VISCOSITY (b) (Continued in next page)

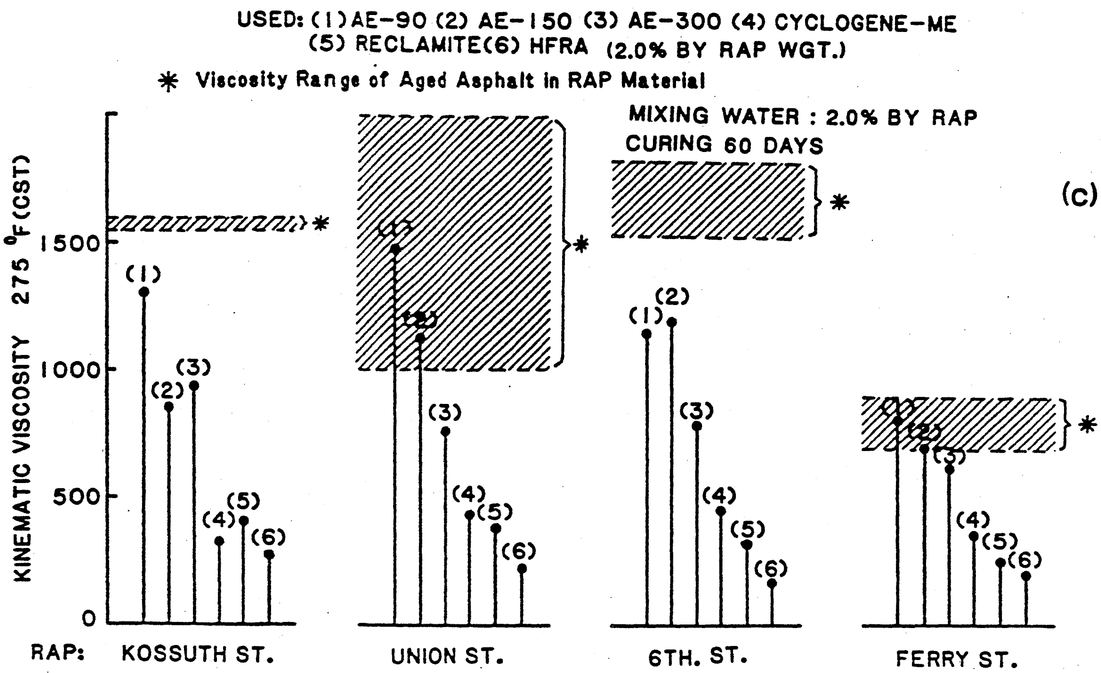


FIGURE 4.11.- EFFECTS OF VARIOUS RECYCLING AGENTS UPON PENETRATION (a), ABSOLUTE VISCOSITY (b) AND KINEMATIC VISCOSITY (c) OF THE EXTRACTED ASPHALT RESIDUE FROM VARIOUS RAPs (Continued from previous page)

agent was added to the RAP. These effects were consistent with the degree of hardness or softness of the agent used. Hard residue agents increased the penetration of recovered asphalt by a much smaller amount than did soft residue agents. The trends in viscosity of the recovered asphalts were different, with hard residue agents decreasing the viscosity of recovered asphalts by less amounts than those obtained using softer residue agents.

All this tends to indicate that after an appropriate period of time, long enough to allow the modifying effect of the recycling agent to take place throughout the recycled mix, the characteristics of the new binder or recycling agent are eventually going to modify the original binder to a point where it would have a more flexible and ductile behavior than it originally had. These modified properties would largely depend on the properties and amounts of the recycling agent used.

<u>Curing Time</u>.- The effects of various curing times were analyzed using non-destructive types of test procedures that allowed the same specimen to be tested at different curing time intervals. The results from these tests were as follows:

(a) All the test parameters measured increased with the increase in curing time. The largest increments were observed within the first 10 days of curing at room temperature (+/- 72 deg.F). This initial stiffening of the mix was caused by the evaporation of the water from the recycling agents added.

(b) Overall, slightly higher pulse velocity values were obtained for specimens with 2.0% agent content as compared to samples with 1.0% only (Figure 4.12-a and 4.12-b).

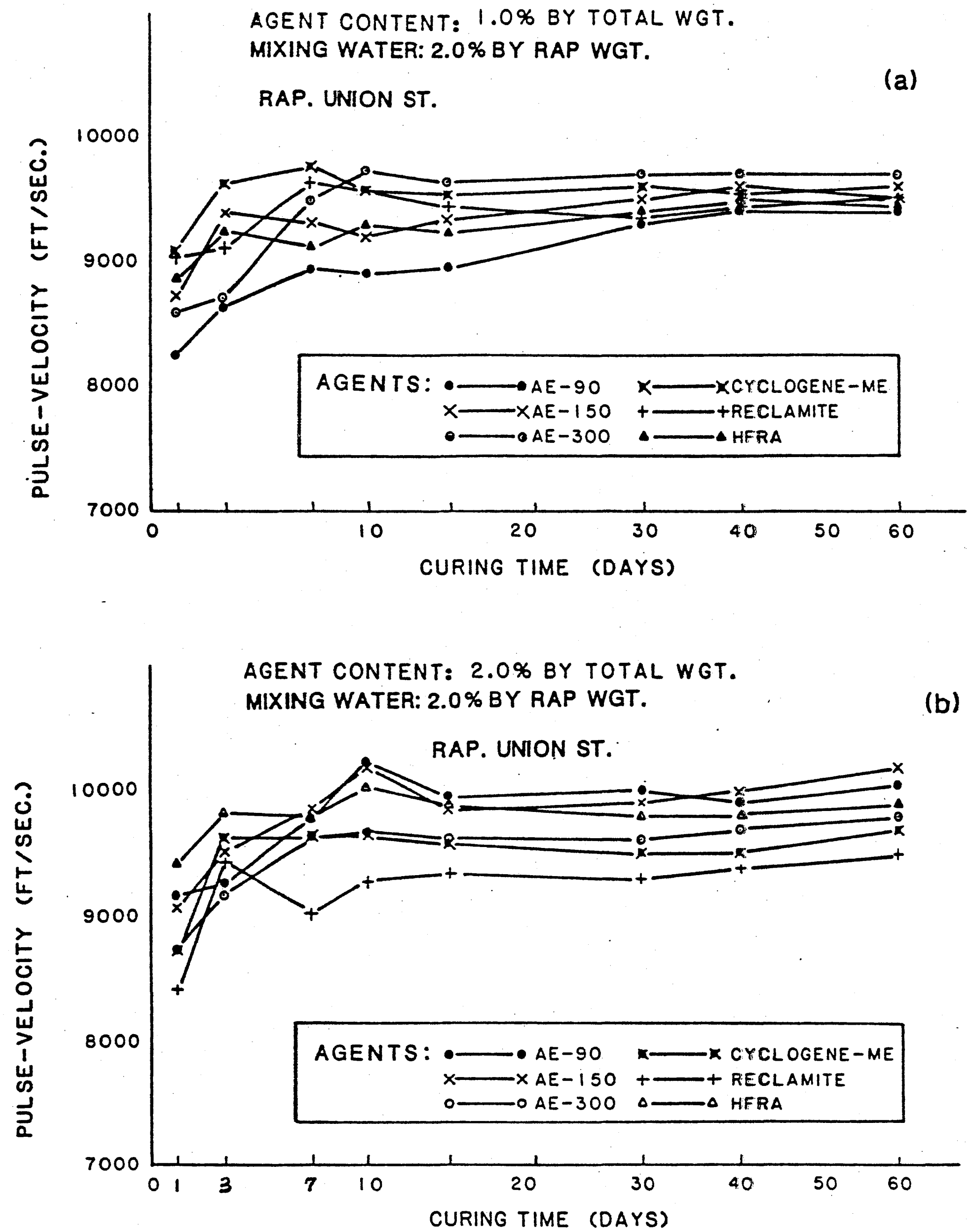


FIGURE 4.12- CURING TIME VS. PULSE VELOCITY OF MIXES WITH 1.0 % (a) AND 2.0 % (b) RECYCLING AGENT CONTENT

(c) The trends observed for the resilient modulus were reversed with higher resilient modulus observed overall for specimens with 1.0% (by total weight), as compared to samples with 2.0% agent added (Figure 4.13-a and 4.13-b).

(d) Mixes prepared with the softer residue agents did not necessarily follow the trends indicated above. In some instances, the resilient modulus or pulse velocity of the mix decreased or had a very slow increase in value after the first few days of curing (especially when Reclamite was the recycling agent). Previous studies showed the same trend of resilient modulus [50, 67], in which test data supported the idea that a softening effect takes place after there is a diffusion of the recycling agent into the old asphalt cement.

4.4 - Effects of Various RAP Gradations

Common to all recycling operations is the need to remove the aged asphalt pavement material and reduce it to a size or gradation suitable for mixing and paving operations. The RAP gradation may vary depending on the type of equipment and process used in breaking up or milling the existing asphalt pavement.

The cold planing and/or cold milling process can be associated mainly with city streets recycling operations where recycling work tends to be more specific and restricted in size. The breaking up (ripping) and/or scarification process is more common in longer recycling sections as the ones related with county roads. These two forms of processing the aged asphalt pavement produce substantially different RAP chunks and particles size.

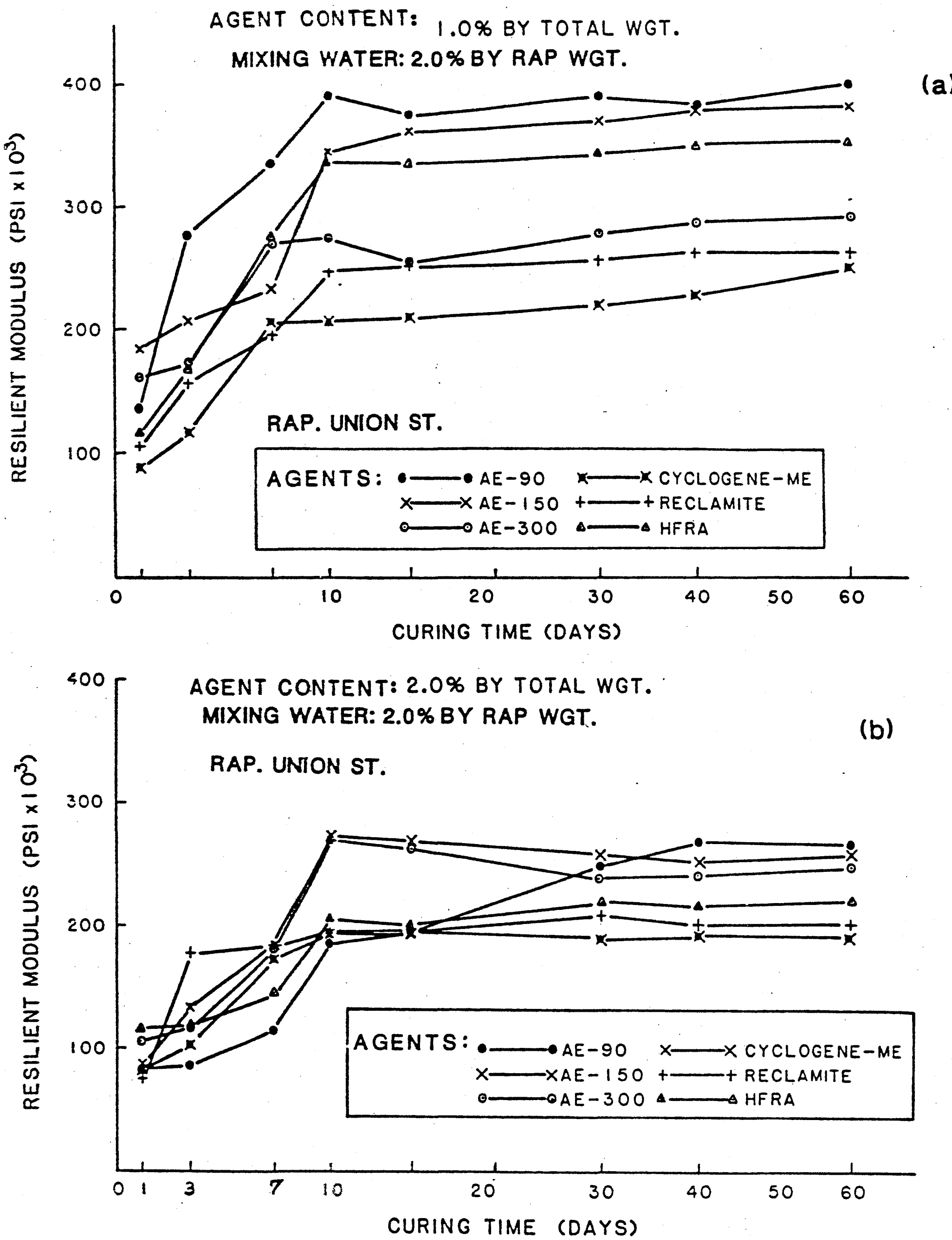


FIGURE 4.13.- CURING TIME VS. RESILIENT MODULUS OF MIXES WITH 1.0 % (a) AND 2.0 % (b) RECYCLING AGENT CONTENT

The effects of the gradation of the reclaimed asphalt pavement (RAP) material upon the behavior of the final recycled mix appeared to be of some concern according to previous publications [11, 31, 33, 35, 37, 38, 48, 52, 53, 55, 79, 80, 81, 82].

The tailings or cuttings generated by the cold milling process are normally sized to the desired gradation (1 to 2 inches) and can be used to produce a recycled mix without further processing, with the possible exception of scalping of oversized pieces of RAP. However, one of the major concerns associated with utilizing cold milled material in cold-mix recycling operations involves the increased amount of fine material generated by the milling process [33].

Ripping and scarification is the most common method used to loosen and break up the existing pavement if the total bituminous layer is to be removed. Depending on thickness, age and material integrity of the asphalt pavement being removed, a wide variety of motor grader or tractor-mounted scarifiers or rippers can be used. Following scarification or ripping, the salvage material can be either crushed in place or hauled to a central plant for further processing.

The use of aggregate crushers for reducing the size of these RAP materials was of early concern. The aggregate degradation that could take place during the crushing operation appeared to be minimal, with some fracturing of large aggregate particles [33, 81]. Fracturing or breakage of the asphalt concrete matrix principally occurs in the asphalt cement rather than the aggregate. The resultant product of the crushing operation is a mixture of asphalt coated discrete particles and asphalt-aggregate aggregations.

In addition to these processes that generate RAP material of varying gradation and amounts of fines, the problem of stockpile segregation and agglomeration is also associated with salvaged asphalt concrete. Agglomeration is the adhesion of the crushed or milled material into a larger aggregation than desired, and it may result if the material is stockpiled for too long a period of time before use [81]. Stockpile segregation is the separation of the coarse and fine fractions of the crushed materials. Segregation normally occurs from poor stockpiling techniques. Limiting the construction of salvaged material stockpiles to a maximum of 10 feet [81], has helped to alleviate this problem.

A wide range of standard gradations were selected in order to determine the effects, if any, of RAP size in the performance of cold recycled mixes. These gradations ranged from fine to coarse, according to their calculated aggregate gradation modulus (A) (refer to Section 3.3 of this report). They represent typical cold-mix aggregate gradations used in the State of Indiana. Table 4.9 and Figure 4.14 present the corresponding information for these RAP materials.

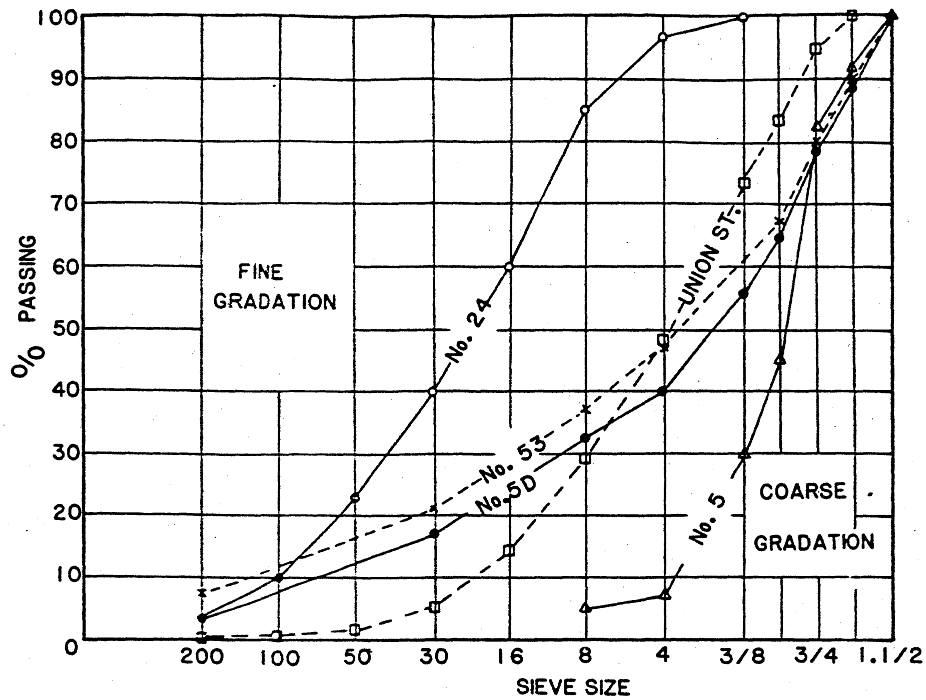
Discussion of Test Results.- It can be stated that the range (8.2 to 3.5) of gradations used in this part of the laboratory analysis was large enough to demonstrate, through test results,

TABLE 4.9.- EFFECT OF VARIOUS RAP GRADATIONS (GRADATIONS USED)

Sieve Size	Mid-range RAP Gradation (% passing)				
	No. 24(*)	No. 53(*)	No. 5D(*)	Union St.	No. 5(*)
1.1/2 in	100.	100.	100.	100.	100.
1	100.	90.	89.5	100.	91.5
3/4	100.	80.	79.	95.	72.5
1/2	100.	67.5	65.	83.	45.
3/8	100.	-	56.	73.	30.
No. 4	97.5	47.5	40.	48.	7.5
8	85.	37.5	32.5	29.	5.
16	60.	-	-	14.	0.
30	40.	21.	17.5	5.5	0.
50	23.5	-	-	2.	0.
100	10.5	-	-	0.5	0.
200	3.	7.5	3.	0.2	0.

Agg. Grad.:	No. 24(*)	No. 53(*)	No. 5D(*)	Union St.	No. 5(*)
	Aggregate	Gradation	Modulus	($\bar{A}$)	
$\bar{A}$ =	8.2	5.7	5.3	5.3	3.5

* Note: Typical Cold-Mix Aggregates Gradation
Indiana Department of Highways, 1985 Standard Spec's.



NOTE: Gradations No.24, No53, No5D, and No5, are the midpoint of the 1985 Indiana DOH specifications band.

FIGURE 4.14.- RAP GRADATION EFFECTS - GRADATIONS USED

if there is any significant effect of the RAP particles size distribution in the final behavior of cold recycled mixes for Indiana asphalt pavements.

The main findings of this part of the study were as follows:

(a) Resilient modulus and Marshall stability results were influenced by the difference in gradation of the RAP material used (Figures 4.15 and 4.16). An interaction effect of gradation modulus and type of recycling agent used was observed when analyzing these two test parameters. More defined trends of resilient modulus and Marshall stabilities were observed for mixtures prepared with the softer residue agent (AE-300). The modulus and stability of the mix seems to increase with the increase of aggregate gradation modulus. This means that the more fines in the RAP gradation, the higher these two parameters would be.

On the other hand, the results obtained using a harder residue agent (AE-90), showed that there is an optimum RAP gradation modulus value where resilient modulus and stability results reached a maximum. This optimum gradation modulus is within the range of values (5.0 and 6.0) reported for conventional standard aggregate gradations [58, 59, 60].

(b) The Marshall stiffness and Marshall index of the mix generally increased with the increase of fines in the RAP gradation, i.e., with the increase in gradation modulus value (Figures 4.17 to 4.19). These trends (Figure 4.19), again, were more evident when softer residue agents were used (AE-300) as compared with the stiffness and index values obtained using harder residue agents (AE-90). These two parameters were almost insensitive to

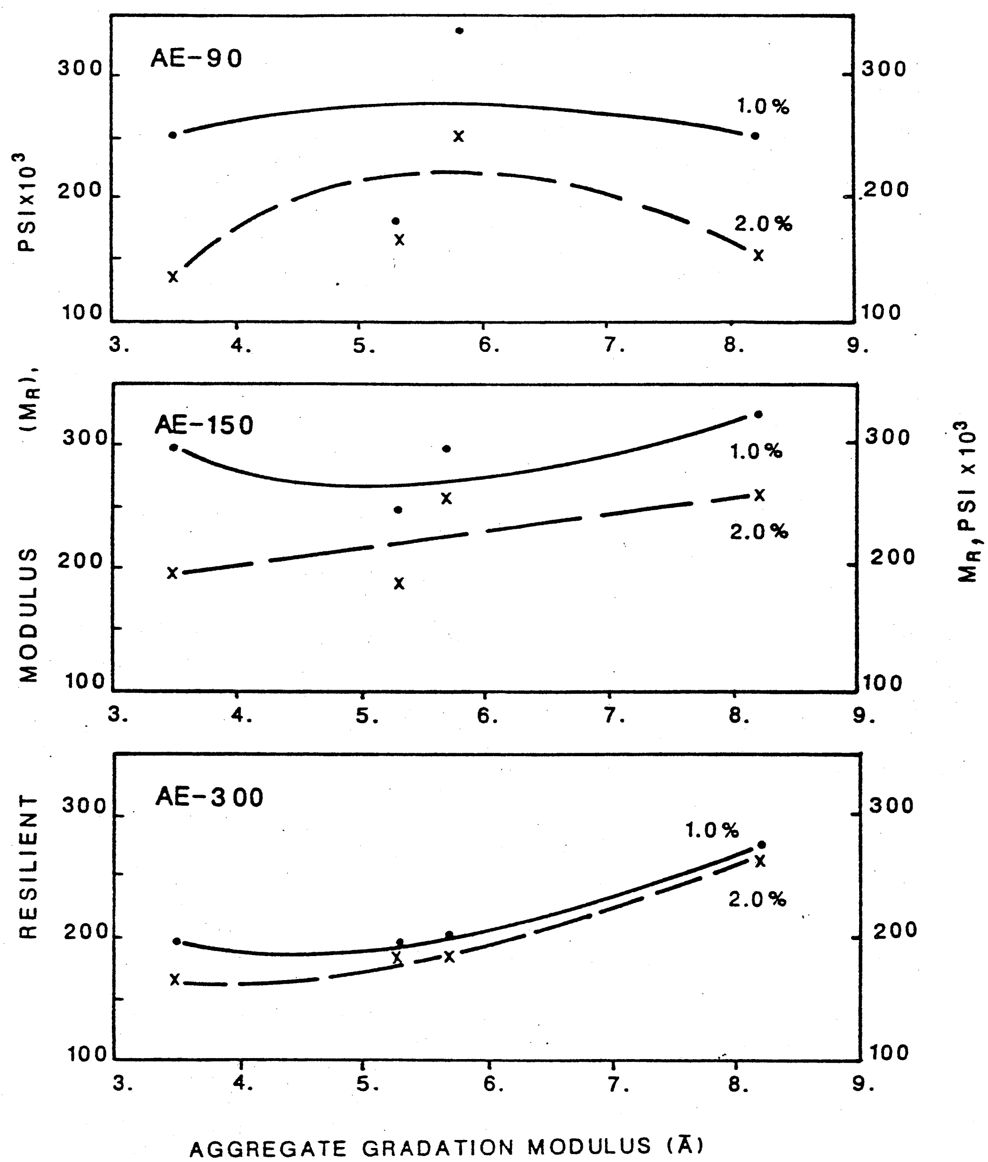


FIGURE 4. 15- RESILIENT MODULUS TRENDS FOR VARIOUS RAP GRADATIONS

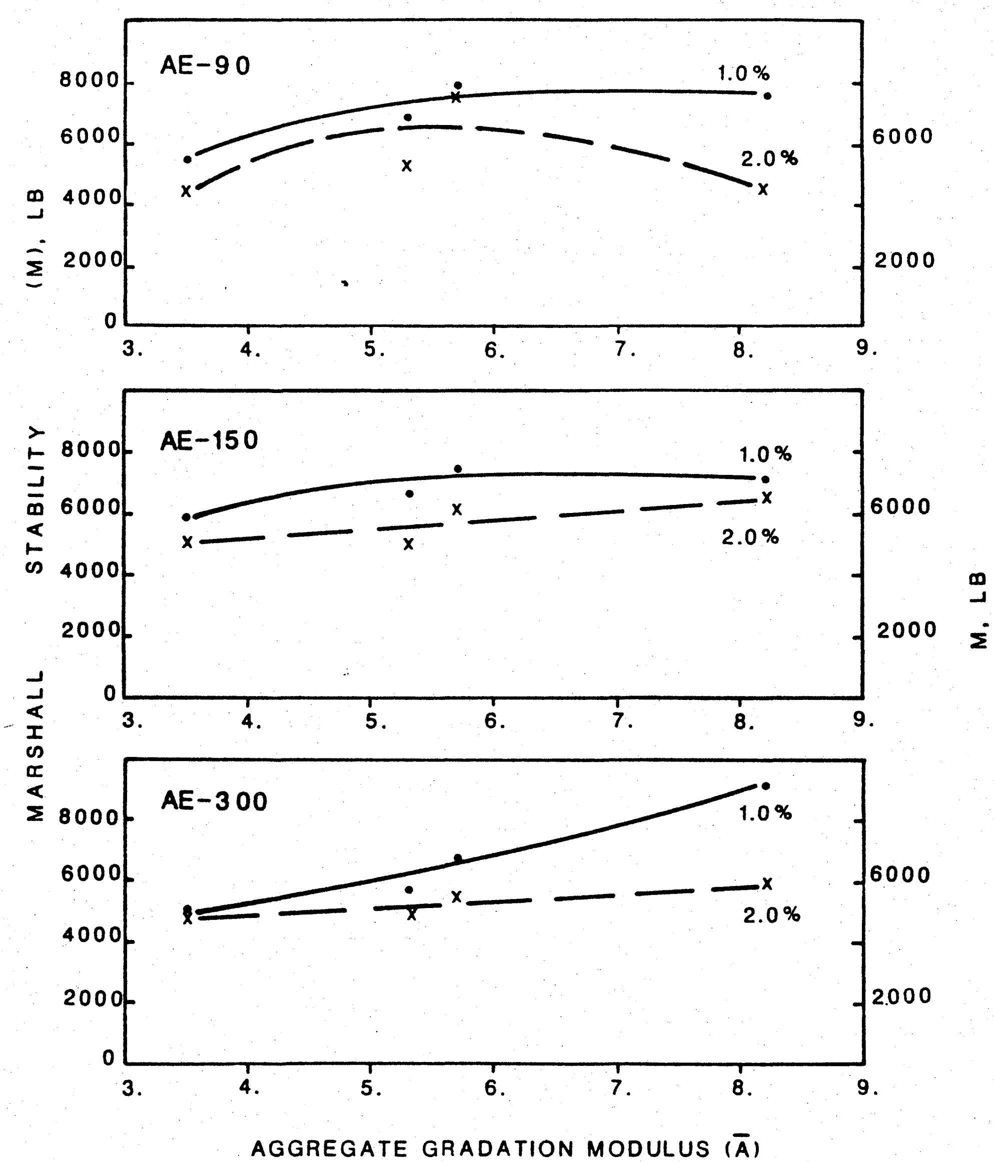


FIGURE 4.16.- MARSHALL STABILITY TRENDS FOR VARIOUS RAP GRADATIONS

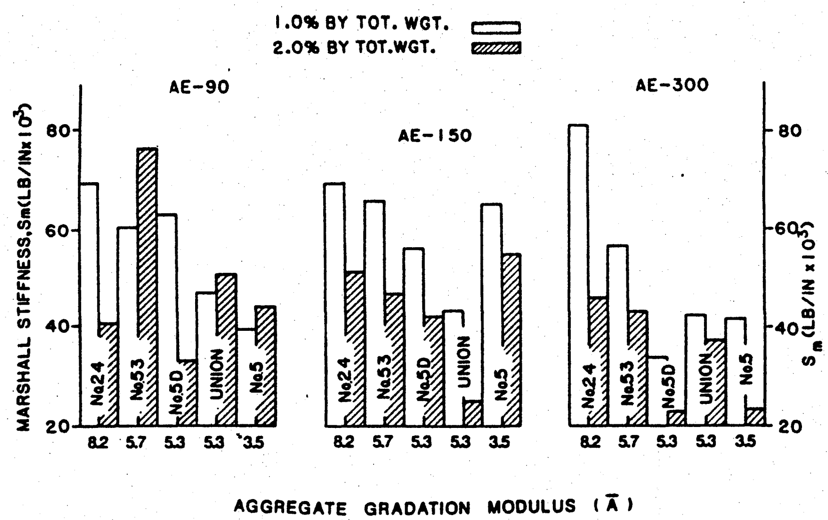


FIGURE 4.17.- AGGREGATE GRADATION MODULUS VS. MARSHALL STIFFNESS

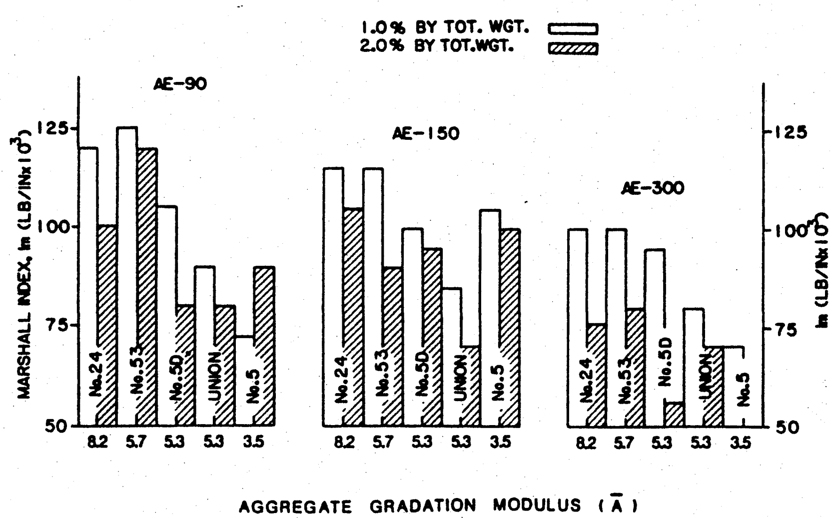


FIGURE 4.18.- AGGREGATE GRADATION MODULUS VS. MARSHALL INDEX

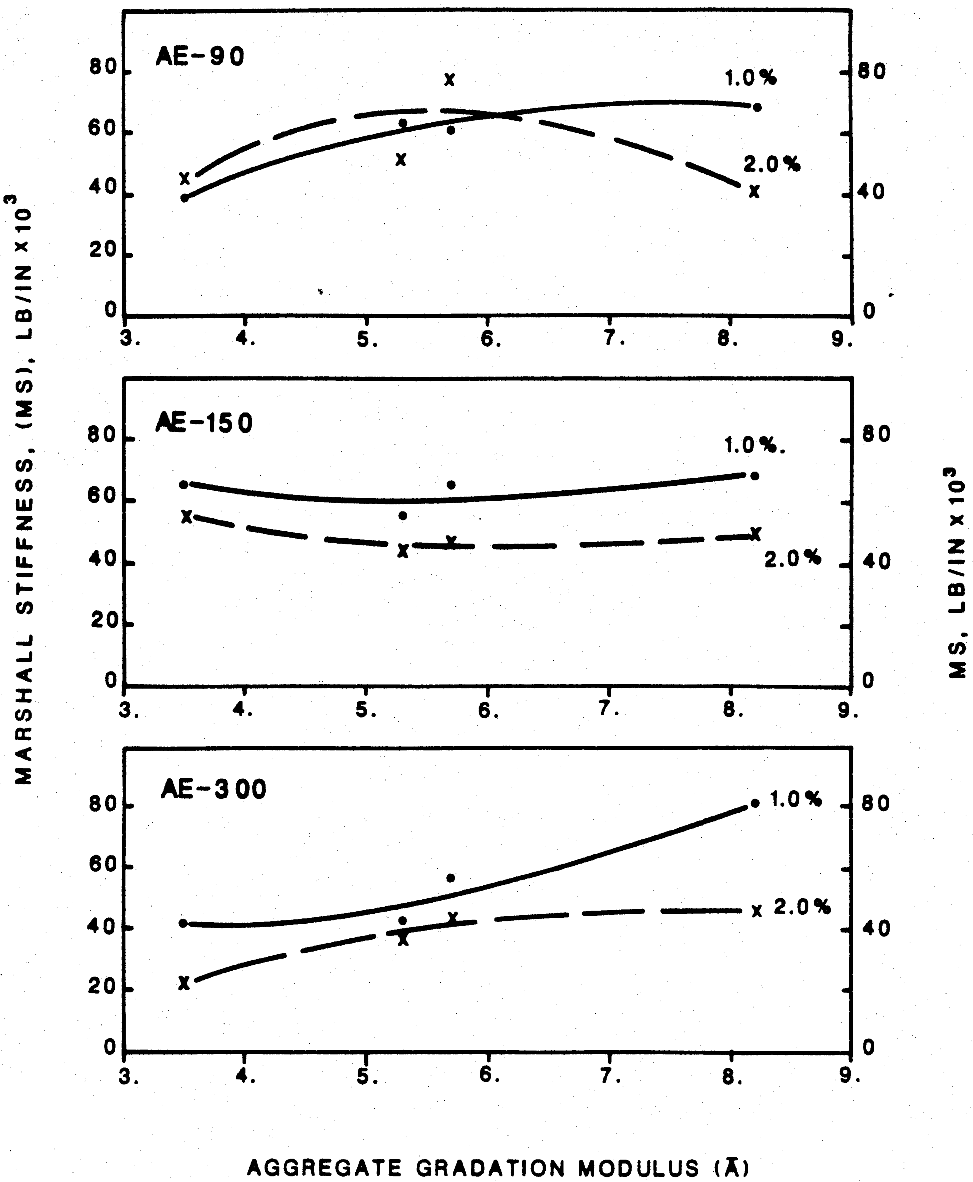


FIGURE 4.19- MARSHALL STIFFNESS TRENDS FOR VARIOUS RAP GRADATIONS

the various gradation modulus used in this study when an AE-150 was the added agent. The changes observed using either 1.0 or 2.0% agent contents showed similar trends.

(c) Finally, the effects of different RAP gradations upon the density and pulse velocity results of the mixes studied were more defined and similar to each other, independently of the type of agent and agent content added (Figure 4.20). Pulse velocity and density results reached a maximum at gradation modulus values within the standard aggregate size range (5.0 to 6.0), at either 1.0 or 2.0% agent content.

4.5 - Effects of Different Aged Binder Contents

This part of the laboratory study was performed using artificially aged asphalt paving mixes. The objective of this laboratory analysis was to determine the effects that two different amounts of original binder would have on the behavior of a recycled mix when prepared with various recycling agents.

A better control of the material used was desired, so an artificially aged hot-mix was used to prepare test specimens. The artificially aged mix was made to resemble old pavement materials reclaimed from a county road or a city street in Indiana. The aggregate used was a common terrace gravel with a mid-range standard gradation, IDOH No. 53 aggregate (refer to Table 4.9, previous Section).

Discussion of Test Results.- The effects of two different binder contents (4.5 and 7.5% by weight of dry aggregate) of the RAP material used were evaluated by means of resilient

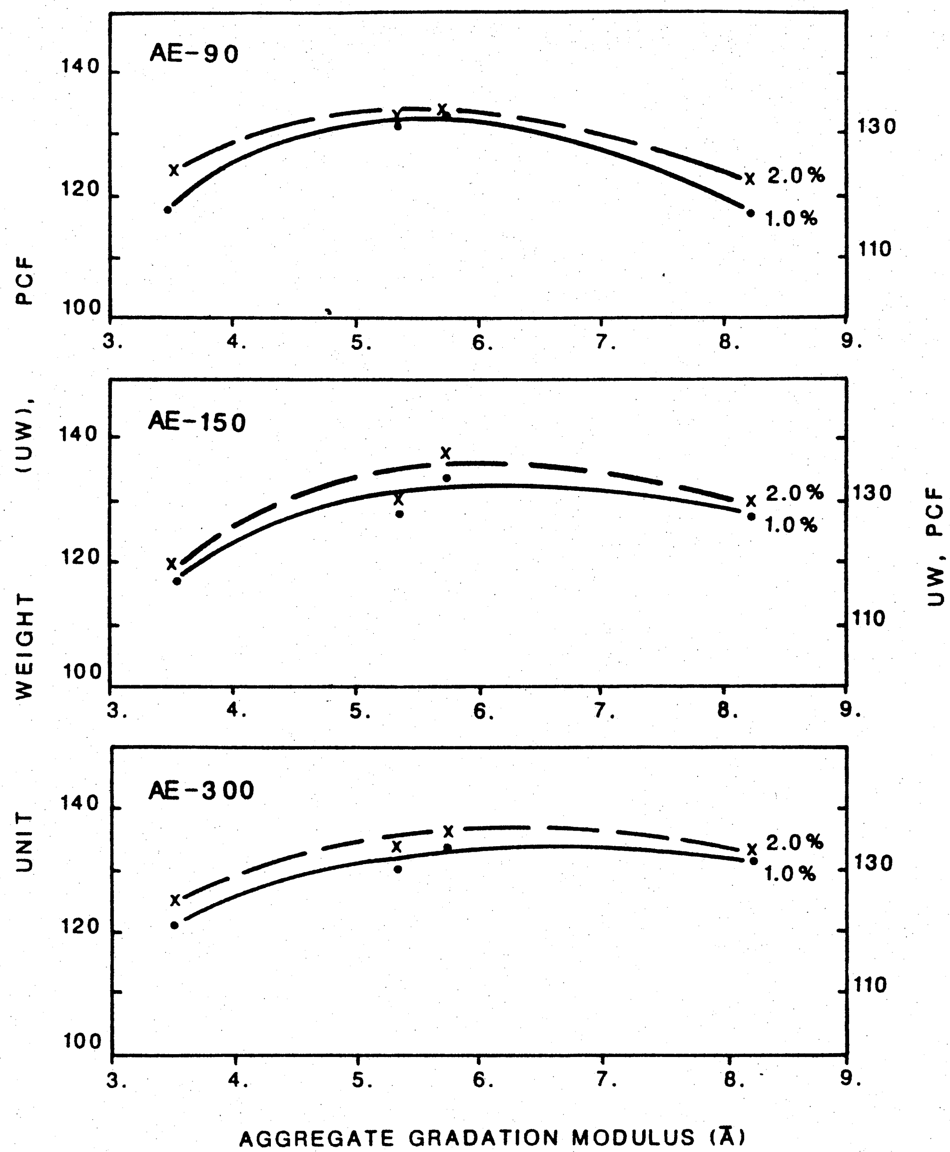


FIGURE 4.20.- DENSITY TRENDS FOR VARIOUS RAP GRADATIONS

modulus, Marshall stability and stiffness, and density of the mix. The findings of this experimental work were as follows:

(a) Resilient modulus results were either the same or decreased when the original (aged) binder content of the RAP increased. Softer residue agents (Reclamite and HFRA, in particular) produced mixtures that were less sensitive to changes in aged binder as compared with mixes prepared with all the other agents.

(b) Marshall stability values were affected by the changes in original binder content of the RAP. The trend was similar to the one described for resilient modulus test results. However, the amounts of agent added to the mix (1.0 vs. 2.0% by weight of RAP), appeared to have a much larger effect than previously noticed. In all the cases analyzed, lower agent contents gave larger Marshall stability values.

(c) The Marshall stiffness of the mix (Figure 4.21) was the most sensitive test parameter to changes in original binder content of the RAP material. In all cases (except for specimens with 2.0% AE-90), the higher the original binder content in the RAP, the lower the Marshall stiffness of the sample.

This tends to indicate that in order to obtain the true effect that various original binder contents in the RAP have upon the stability-flow characteristics of the mix, a combined test measurement such as the Marshall stiffness is necessary. This can be an important parameter to be used to test the relative loss in stability of a final cold recycled mix when different asphalt contents are present in a particular asphalt pavement that is

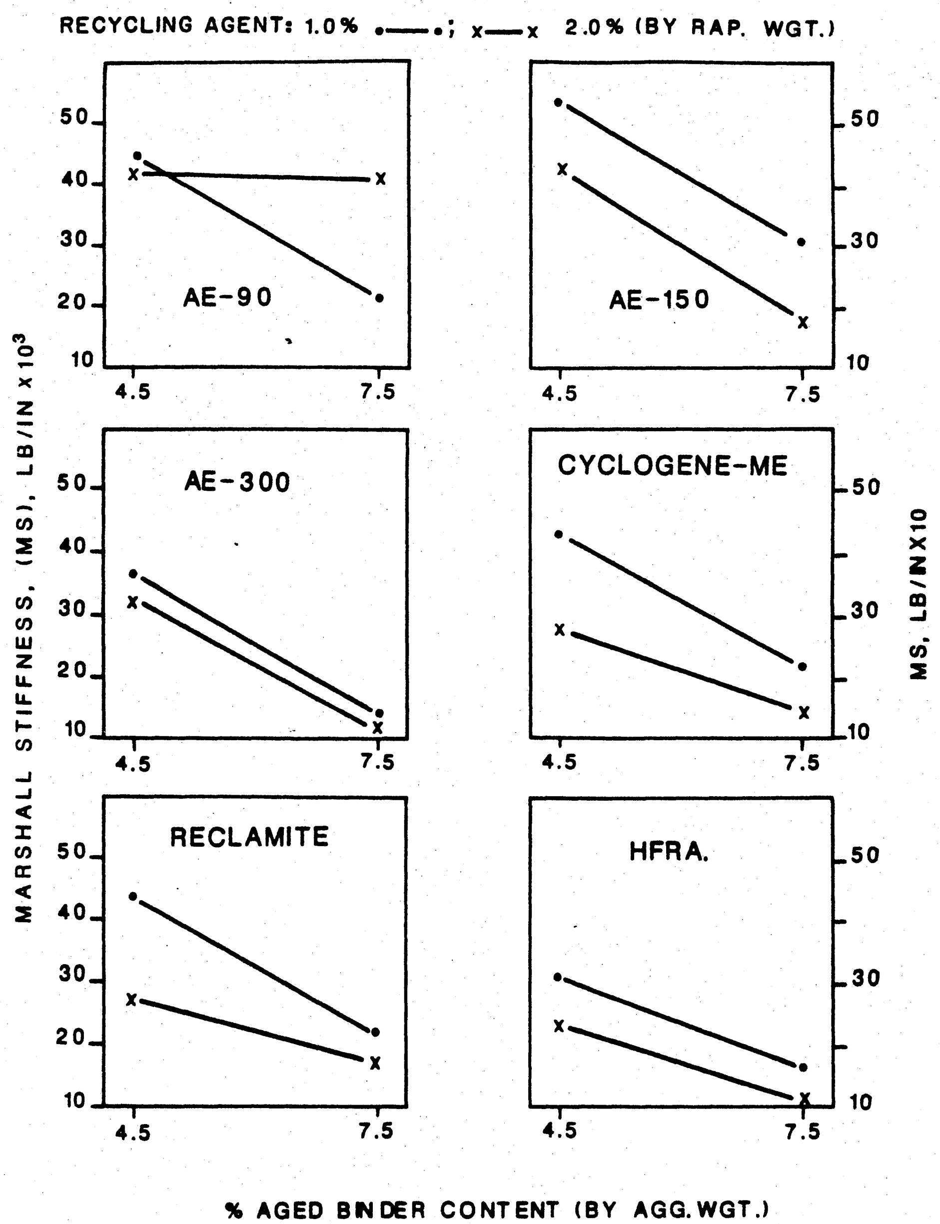


FIGURE 4.21.- % AGED BINDER VS. MARSHALL STIFFNESS

going to be recycled. The range of original binders used here (4.5 and 7.5%) are believed to be well within the range of asphalt contents found in any existing asphalt pavement in Indiana (see Figures 3.6 and 3.7 in Chapter 3).

(d) Finally, the effects of original binder contents upon the density of the final mix were found to be significant for all the types of recycling agents used. The density of the cold recycled mixtures increased with the increase of aged binder present in the RAP. The different effects for 1.0 vs. 2.0% agent added were more evident when softer residue agents were used (Cyclogene-ME, Reclamite and HFRA).

4.6 - Conclusions and Recommendations

The feasibility of recycling existing asphalt pavement materials found in Indiana county roads and city streets was analyzed on a laboratory scale. The scope of this study covered four different RAP materials, six different recycling agents, various RAP gradations, and two aged binder contents, among others.

Conclusions.- The major conclusions from this laboratory study are summarized as follows:

1. Initial mixing water contents of less than 3.0% (by dry weight of the RAP) produced the best performing cold recycled mixes.

2. The levels of recycling agent added have a significant effect on the behavior of the recycled mix. Recycled mixes with agent contents lower than 1.0% (by dry weight of the RAP), showed

inconsistent trends of initial strength or stability properties. This tends to indicate that low agent contents are difficult to distribute uniformly throughout the mix, giving a non-uniform paving material with unpredictable performance in the field.

3. On the other hand, too high agent contents (more than 3.0% by dry weight of RAP), gave unstable mixes that would most likely lead to excessive deformations and bleeding in pavements when such a high agent content is used. The ideal range of recycling agent (liquid asphalts and/or modifying oils or chemicals) for the reclaimed asphalt pavement materials used in this study, appears to be somewhere between 2.0 and 3.0% by weight of the dry RAP.

4. An aeration period prior to compaction and after the mixing of moisture and agent added to the RAP, seems to be necessary to lower the total fluids content of the recycled mix. This initial period was found to produce compacted recycled mixtures with high early strength and stability for better withstanding any handling in the laboratory, or traffic loads in the field.

5. Laboratory specimens compacted with 60 revolutions and 200 psi. in the gyratory machine produced adequate samples for laboratory mix design purposes. This is a recommended setting if the gyratory machine is used to prepare cold-mix recycled specimens.

6. The choice of what type of recycling agent, modifying oil, rejuvenating or softening agent, etc., is the most adequate to be used in a particular cold-mix recycling project, should be first based in the economic aspect and availability of these materials.

All of the six agents used in this laboratory study performed well in altering the hardness of the aged asphalt and producing recycled mixtures with characteristics similar to those of cold-mix made with virgin materials.

7. The effect of curing time was found to be significant. In the first seven days curing at ambient conditions, the increase in strength and stability of the mix was related to the characteristics and amounts of agent added. Softer residue agents would produce early-cured recycled mixtures of low or even decreasing stabilities until the evaporation of the water and other fluids start taking place. Harder residue recycling agents would yield higher stability and strength values initially. All test parameters measured for the recycled mix at various curing times, increased up to a maximum value until they leveled off thereafter.

8. The effect of the RAP gradation was found to be significant at the levels used in this laboratory analysis. However, it was found that cold recycled mixtures produced with RAP gradations within a gradation modulus range of 5.00 and 6.00, would yield mixtures with characteristics similar to those where the RAP material used was processed to include more fines, i.e., larger gradation modulus values. The effects of the RAP gradation were found to further depend on the type of agent used as well as on the amounts of it present in the recycled mix.

9. Finally, recycled mixtures prepared with aged RAP materials of varying original asphalt contents were found to yield different performing paving materials. The Marshall stiffness was

found to be the most sensitive laboratory test parameter for detecting the behavior of these mixes. In most cases, the higher the original binder content the lower the Marshall stiffness of the final recycled mix.

Recommendations.- The main purpose of this laboratory study was to determine the effects that important variables have on the performance of cold recycled asphalt mixtures prepared with materials from Indiana county roads and city streets asphalt pavements. A detailed set of guidelines for cold-mix recycling operations is presented in Chapter 6 of this report. The recommendations outlined next, are merely concerned with the results reported in this chapter.

The findings of this laboratory work are expected to help with the decisions to be made concerning proportioning and types of ingredients for cold recycled asphalt paving mixtures. Based on these findings, it is suggested that the following recommendations be considered by county and local highway engineers for undertaking a sound and cost-effective recycling operation:

1. The degree of oxidation or brittleness of the original asphalt to be recycled must be known. This is obtained by extracting and then recovering the aged asphalt of the RAP. The harder the recovered asphalt, the softer the residue of the recycling agent to be used must be. Common liquid asphalt emulsions were found to perform just as well as commercially available chemicals and modifying oils. The choice between these commercial products

should be made by the engineer first on an economic basis. Second, after narrowing the alternatives to three or more parti cular products, laboratory analysis of recycled mixes prepared with available RAP and the selected recycling agents should be performed in order to chose the particular agent that produces the best performing recycled mixtures.

2. The strength and stability properties of the recycled mix should be evaluated after a sufficient curing period has been given to the laboratory specimens in order to obtain the true maximum strength and stability values for that particular mix. Oven curing at 140 deg.F for 3 days can be considered in order to accelerate the curing process; seven days out of the mold may also be used for this purpose.

3. Optimum mixing moisture and agent contents should be determined using trial mixtures and test procedures described in this chapter. Too high (more than 3.0%) or too low (less than 1.0% by weight of dry RAP) amounts of these two fluids should be avoided since it was found that they produce unstable and weak mixtures as well as mixtures with unpredictable behavior.

4. The findings of the effects of RAP gradations indicated that an existing asphalt pavement reclaimed or salvaged with the use of conventional methods and equipment, does not need extra processing if the gradation being produced by the milling, planing or crushing operation is within the specified 5.0 to 6.0 (+/- 0.5) gradation modulus range.

5. The Marshall stiffness [104] should be used with other laboratory test parameters to evaluate the properties of recycled mixtures when varying amounts of original asphalt content are present in the RAP material to be used. This preliminary evaluation of the final recycled mix would help to determine if the various layers and/or sections within a recycling project area should be treated and designed as separate units of the same recycling job.

6. Finally, it is recommended that the cold recycling procedures known to date, be considered by Indiana's county and city highway engineers as one more of the rehabilitation and maintenance alternatives available to them to upgrade and repair the asphalt pavements under their jurisdiction. Expertise and technical support in this area can be obtained from the Indiana Department of Highways - Materials Laboratory; from technical publications available at the HERPICC technology transfer program, and the Bituminous Laboratory of the School of Civil Engineering, Purdue University; as well as from contractors with recycling experience and/or private paving firms.

CHAPTER 5

ECONOMIC CONSIDERATIONS IN COLD-MIX ASPHALT RECYCLING

One of the major criteria that determine whether a new process will be accepted or not, is economics. If it can be demonstrated that recycling of asphalt pavements has economic advantages over new material construction, recycling can be accepted as a viable rehabilitation alternative.

Factors involved in the economics of asphalt pavement recycling are discussed in this chapter in an attempt to identify the primary elements that control the relative cost of asphalt pavements cold recycling. Data and examples from recycling projects in Indiana and elsewhere, on cost effectiveness, energy consumption, and other conditions necessary for an economic evaluation, are considered. The term "Cold-Mix Recycling" as used in this research, applies for either Cold In-Place Recycling (a process most likely to be adopted to rehabilitate county or secondary rural roadways); Surface Cold Recycling, and Central Plant Cold-Mix Recycling (for urban rehabilitation).

Cold-mix recycling, in general, involves the reuse of existing surface, base, subbase and/or subgrade materials. These materials can be reprocessed in-place or they can be removed and processed in a central plant without heating. Recycling agents can be used during this process. After the pavement has been pulverized, mixed and placed, it normally requires a new wearing surface such as a surface treatment or a hot-mix asphalt overlay [3]. The major advantages and disadvantages of cold recycling operations were compared to other major forms of recycling in Table 1.2 of Chapter 1 of this report. These cold recycling procedures have been described in more detail in Chapters 2 and 4 of this report.

Graphs and tables are presented throughout this chapter in order to highlight the main differences in terms of materials and construction cost as well as energy savings that exist between conventional asphalt pavement rehabilitation methods and the recycling process. Some of the cost figures used to create these graphs and tables were obtained from data reported in the literature adjusted to 1985 prices by means of common cost index methods. Current data were obtained through telephone conversations and personal interviews conducted by the author of this study with highway authorities familiar with recycling and highway construction practices in general. It is expected that the information contained herein would help the highway engineer in the selection of the most economically feasible alternative for rehabilitating a distressed asphalt pavement from a set of options that includes cold-mix recycling.

5.1 - Main Cost Factors in Asphalt Pavement Cold Recycling

The main economic advantage that recycling appears to have over new material construction is in the area of raw materials required for the project. Since the recycling process re-uses materials already on the roadbed, little or no new materials have to be purchased. The salvaged material removed from the asphalt pavement has an intrinsic value which can be attributed to the asphalt and aggregate components of the old pavement. Main cost components in typical highway maintenance and rehabilitation alternatives are: materials, equipment and labor. Table 5.1 is a summary of the relative effects of each one of these factors on the total cost of the rehabilitated pavement.

New materials in cold in-place recycling were reported to account for almost half the total cost; however, almost all the projects' cost figures reported showed that this cost was for the new binder and/or recycling agent used to restore the properties of the aged binder present in the existing pavement and not for virgin aggregate and binder materials, as in the case of hot-mix overlay or chip and seal.

The other two main components of recycling costs are labor and equipment rental and wear. Reports on typical cold in-place recycled asphalt pavements [19, 26, 28, 46] indicated that labor may account in average for about 24% of the total cost of the recycled pavement (Table 5.1). Equipment rental and use are responsible for an average of less than 30% the total project

TABLE 5.1.- COST BREAKDOWN FOR VARIOUS REHABILITATION ALTERNATIVES

In-Place Cold Recycling

Reference No.	[19]	[26]	[28]	[46]	Average
Labor:	20.6%	41.2%	15.2%	17.9%	23.7%
Equipment:	22.7%	25.9%	30.8%	39.5%	29.7%
Materials:	56.7%	32.9%	54.0%	42.6%	46.6%
Total :	100.%	100.%	100.%	100.%	100.0%

Hot-Mix Asphalt Overlay

Labor:	4.7%
Equipment:	4.8%
Materials:	90.5%
Total :	100.0%

Chip and Seal

Labor:	9.5%
Equip. & Materials:	90.5%
Total:	100.0%

cost. These two cost components for hot-mix overlays and chip seal rehabilitation alternatives were reported to be much lower than for recycling.

Because cold recycling cost information is obtained from various sources computed at various times, it is necessary to bring these costs to a common time frame. In order to convert the cost figures presented in this report to a current date, the cost index method suggested by the Engineering News Record (ENR) [98], was used. Annual averages of construction cost indices presented in Table 5.2 were used to update these cost data.

The index number to use depends on the type of cost being estimated. Four indices are given in the related literature from which to choose. They are: (1) The ENR general purpose "Construction Cost Index", and (2) the ENR "Equipment Cost Index" [98]; (3) the FHWA "Price Trends for Federal-Aid Highway Construction" [99], and (4) the FHWA "Highway Statistics" [100].

5.2 - Factors Affecting the Economics of Asphalt Pavement Materials Removal

Since more than 80 % of the asphalt mixtures produced are purchased by public highway agencies [81], one can assume that potentially this amount of all recyclable materials will come from public roads. Hence, the attitude of these highway agencies (mainly local highway agencies) towards recycling is all influential in motivating the necessary equipment purchases and modifications to do recycling by local contractors.

The entire procedure of removing pavement materials and reprocessing them through recycling techniques to subsequent replacement in the pavement is usually compared against other alternatives such as an asphalt overlay. It can be argued that pavement material removal can be done independently of recycling and vice-versa. In any event, the economics attributed to the removal and reprocessing of asphalt pavement materials is related to the following considerations:

1. The salvage value of the reclaimed pavement materials is equal to the cost of an equal quantity of new aggregates and asphalt cements, less the cost of pavement material removal and processing.

2. Some savings can be realized through recycling pavement materials for not having to reposition manholes, guardrails, overhead signs, bridges, curbs, gutters, raising shoulders, and so on.

3. According to Smith [90], the recycling ratio, which is the ratio of the amount of material removed to the amount of material replaced, is a very influential factor on the economics of asphalt pavements recycling. If this ratio is greater than 0.7 (i.e., 30 % reclaimed and 70 % virgin paving materials), there may be excess reclaimed material left over after the project is completed. The economic value (salvage value) of this excess material is dependent on whether there is another place to use it within a reasonable hauling distance.

TABLE 5.2.- ENR CONSTRUCTION COST INDICES [98]

Annual Year/Avg. :	Annual Year/Avg. :	Annual Year/Avg. :
1913: 100	1971:1581	1979:3003
. . .	1972:1753	1980:3237
. . .	1973:1895	1981:3537
1966:1019	1974:2020	1982:3825
1967:1070	1975:2212	1983:4055
1968:1155	1976:2401	1984:4148
1969:1269	1977:2577	1985:4177
1970:1385	1978:2776	

Note: ENR builds the Indices according to the average labor rates and material average prices as described in Reference No. 98.

Annual Average Cost Index for 1985 is the average of the Index for the months of January, February and March, 1985.

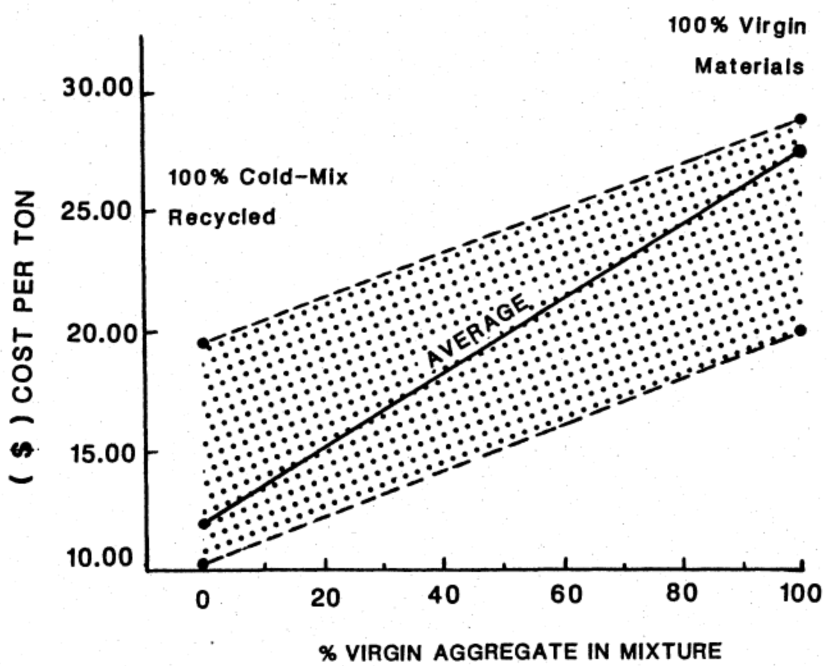


FIGURE 5.1.- EFFECTS OF VARYING AMOUNTS OF VIRGIN AGGREGATE ON THE FINAL COST PER TON FOR ASPHALT MIXTURES

4. The salvage value is further affected by the nature of the reclaimed materials such as gradation variability, type of aggregate, hardness of the original asphalt binder, and other material related factors.

5. Finally, the reclaimed material ownership policy and the existence of permissive recycling specifications contributes to the economics of the reclaimed asphalt pavement (RAP) material.

In the event where pavement material removal was performed because there was no other alternative available, (the base course had failed and additional overlays would have been fruitless), the salvage value of the removed materials is equal to the cost of new replacement materials. This situation illustrates where pavement materials can be removed assuming a zero salvage value. That is, they will be removed regardless of any recycling to be done. Typically, these materials are disposed of in landfills, or the contractor stockpiles them at his plant sites with little opportunity to use them.

A public highway agency can obtain additional benefits from these stockpiled materials by permitting the use of these reclaimed materials in the asphalt mixtures. As can be seen in Figure 5.1, the cost of the mix increases with the addition of virgin aggregate; on the other hand, the cost decreases with the increased amounts of reclaimed material used. The range of values shown in Figure 5.1 are for 100% cold-mix, in-place (lower band) recycled material, and 100% central plant, cold-mix (upper band) recycled asphalt mixture. The price range for cold-mix base course asphalt mixtures prepared with 100% virgin aggregate is presented on the right hand side of this graph. These cost figures were developed in the present study on the basis of information obtained from the IDOH, a local contractor, and recently published data on cold-mix recycling construction costs [18, 46].

Several state highway departments are reportedly allowing the addition of reclaimed materials to base course mixes provided that conventional mix specifications are still met; but, since the use of reclaimed materials in surface courses is still considered experimental, there is practically no use of these materials in asphalt pavements wearing course.

5.3 - Cost Comparison Between Cold In-Place and Commonly Used Rehabilitation Procedures for Secondary Roads

When faced with the task of rehabilitating a roadway, the county or city highway engineer has usually two practical and common alternatives to select from: a hot-mix asphalt overlay or a surface treatment. These two operations generally provide a temporary solution to the distresses that affect the pavement performance. They are selected either because of budget constraints, or because the technology existing in the area (also equipment and experience), is related to these types of applications, or both.

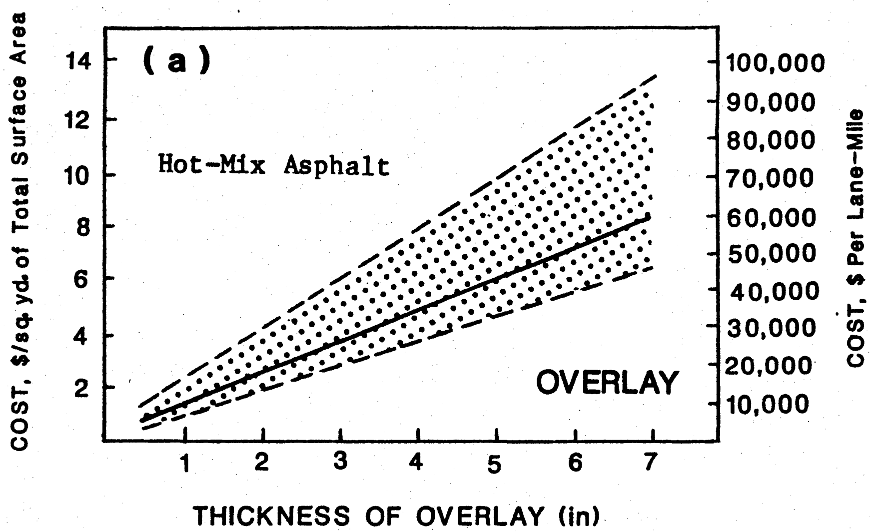
In most cases, single surface treatments, or chip and seal, is a less expensive short term solution for most distresses that affect secondary and low volume roads. This process does not provide structural improvement to the treated asphalt pavement and often lasts for a period of two to three years (or less) before new maintenance is required.

An extensive search of the literature revealed an approximate range of prices for hot-mix asphalt overlays and cold in-place base course materials (Figure 5.2). This range of values was obtained for cost per square yard of various inches of finished pavement. The data shown in Figure 5.2 (a) were updated from a similar graph presented in Reference 10. Figure 5.2 (b), (cold in-place recycling base materials), was constructed from data reported in the literature as well as from information obtained at the FHWA Region 15, Demonstration Projects Program, and telephone conversations with personnel of the Illinois DOT - Bureau of Local Roads and Streets.

5.4 - Energy Requirements in Cold Recycling of Asphalt Pavements

There are several types of roadways that constitute Indiana's highways network. These roads can be divided into four broad classes [10]: (i) interstate and urban freeway, (ii) rural primary (U.S. and state signed routes), (iii) rural secondary (farm to market roads), and (iv) urban streets (arterial, collector, local). Of all these types of roads, rural secondary or county roads and urban streets are the types of roads of most interest in the present study.

County roads (rural secondary, farm to market), are usually recycled by reworking the total pavement and base into a new base with a new surface treatment placed on top of it. Significant



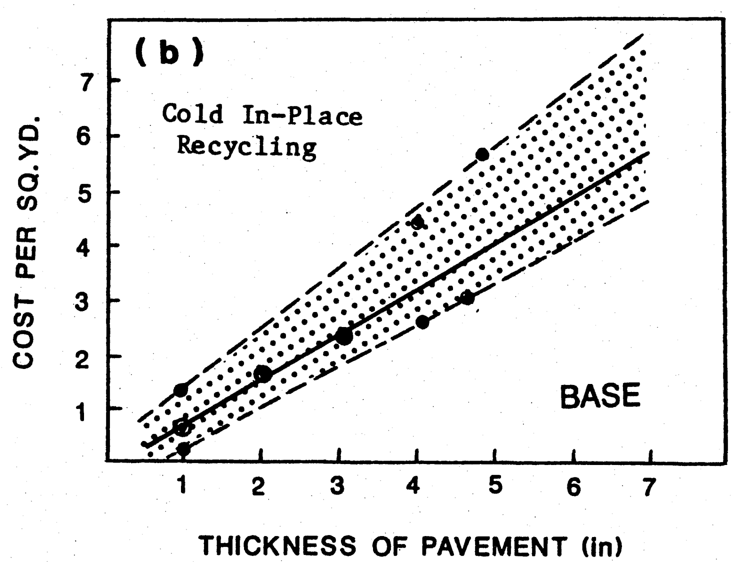


FIGURE 5.2.- COST OF (a) HOT-MIX OVERLAY AND (b) COLD RECYCLED BASE MATERIAL FOR VARIOUS PAVEMENT THICKNESSES

cost and energy savings may result from the elimination of the need to purchase large quantities of aggregate and transport them to the job site (see Table 5.1). Obviously, savings increase significantly as the distance new aggregates must be hauled increases. In-place mixing with road machines or manipulation with graders are most often used on this class of roadway. The use of emulsified asphalt (if any) instead of cutback asphalt or hot-mix plant processing of this type of pavement materials, makes it the most energy efficient, environmentally desirable and less expensive procedure.

Urban street pavements are more likely to be recycled by surface recycling or central plant mixing after cold or hot milling or planning. One significant advantage of recycling in this situation is the elimination of the need for raising levels of manhole covers or correcting the heights of curbs and drains as would be necessary for an overlay. An alternative often considered for this class of asphalt pavements is to remove and stockpile the old surface material for use elsewhere in a less demanding situation as part of a base or surface course for parking lots or alleys. If this alternative is used, the savings in energy and cost are not in the initial project but are realized by salvaging the economic value of the removed material on another project.

Transportation and Construction Energy Requirements:

Transportation and construction energy are two categories of major interest to highway contractors and engineers. These categories consist of the fuel used in hauling materials and in the operation of equipment for processing materials and manufacturing the finished product of the recycling operation.

Conservation in these categories has a direct bearing on reducing or minimizing the costs of highway construction in general. In considering recycling and alternative highway rehabilitation procedures, the energy use in these categories is one of the major considerations in determining the relative costs. As the distance that new materials must be hauled increases, the advantage of recycling significantly increases as would be expected. Energy saved also increases as the proportion of recycled material in the final mix increases.

Table 5.3 lists the expected direct energy requirements of various operations commonly used in cold recycling of distressed asphalt pavements. It should be noted that the energy requirements for the first four operations shown in this table (i.e., cold and hot milling, and heater planing and scarification), only include energy associated with the equipment used for pavement removal. The energy requirements for the last two items of this table (in-place and central plant recycling), include the energy associated with the removal, processing, transportation (central plant recycling only), and finishing operations of the cold-mix

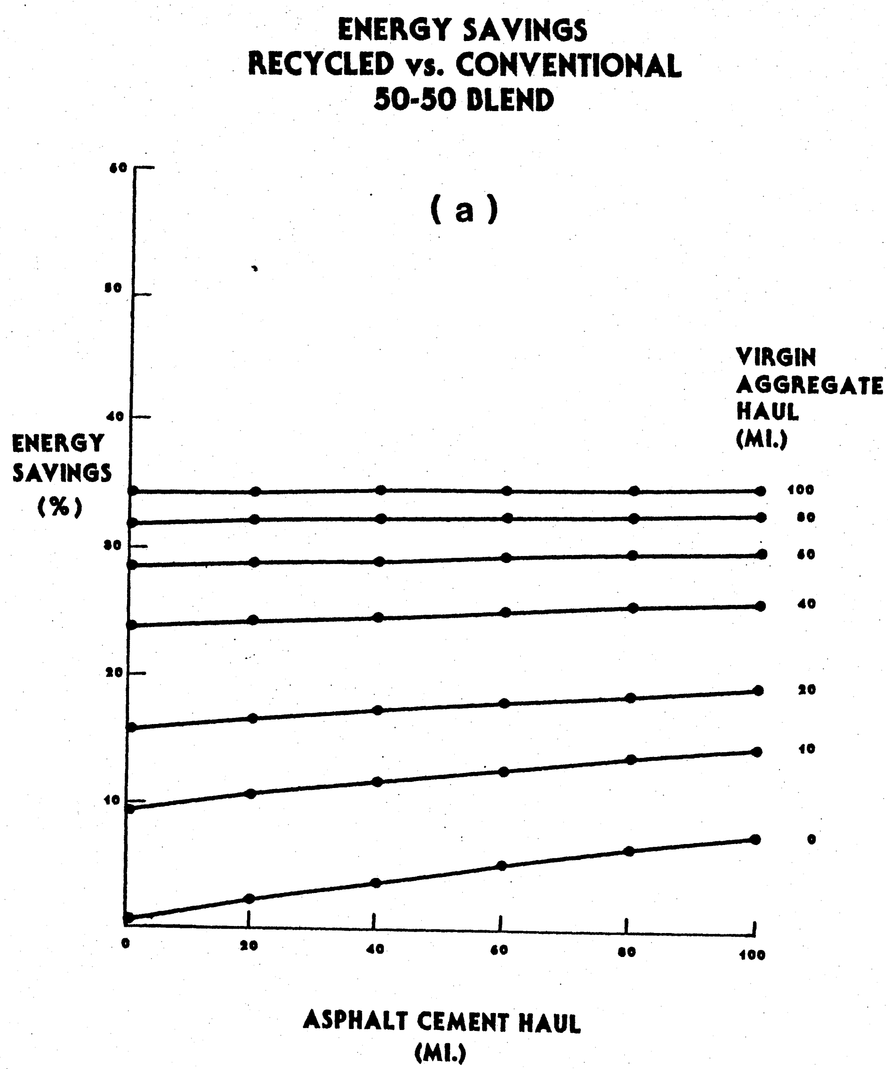
TABLE 5.3- REPRESENTATIVE DIRECT ENERGY REQUIREMENTS FOR ASPHALT PAVEMENT RECYCLING OPERATIONS [3]

Recycling Method	Direct Energy (BTU per syd)	Thickness of Treatment (in)
Cold milling	1,000 - 2,500	1
Hot milling	2,000 - 4,000	1
Heater planing	10,000 - 20,000	3/4
Heater scarification	10,000 - 20,000	3/4
In-place recycling	15,000 - 20,000	1
Central plant recycling	20,000 - 25,000	1

recycled pavement. These values can be used in comparing the economics of various recycling methods with conventional procedures.

The energy savings obtained using In-Place Cold Recycling are illustrated in a series of graphs in this section. These figures (Figure 5.3-a, b, c and d), were prepared assuming that three factors are the major contributors to potential energy savings; namely, virgin aggregate and asphalt cement hauling distance, and the salvaged pavement/virgin aggregate blend. By varying these three factors within reasonable limits and utilizing standard equations, energy factors and basic assumptions recommended in the literature [15, 96], energy savings were computed for different sets of possible project conditions. These graphs are only intended to indicate the approximate energy savings that may be realized on some projects. The information presented in these figures shows that the larger the reclaimed to virgin material ratio (80-20 vs. 50-50), the greater the energy savings obtained for any given combination of asphalt cement and virgin aggregate hauling distance.

Calculations of energy usage in hauling reclaimed asphalt pavement materials (transportation energy) and energy used in construction and processing of these materials (construction energy), were made by Halstead [5, 94] for various assumed conditions associated with Central Plant Cold-Mix Recycling. These results, obtained using pavement energy factors published by the Asphalt Institute [96], are presented in Figures 5.4 (a) and (b).



Source: Adopted from Reference 103

FIGURE 5.3.- ENERGY SAVINGS VS. ASPHALT HAULING DISTANCE: (a) 50-50 BLEND

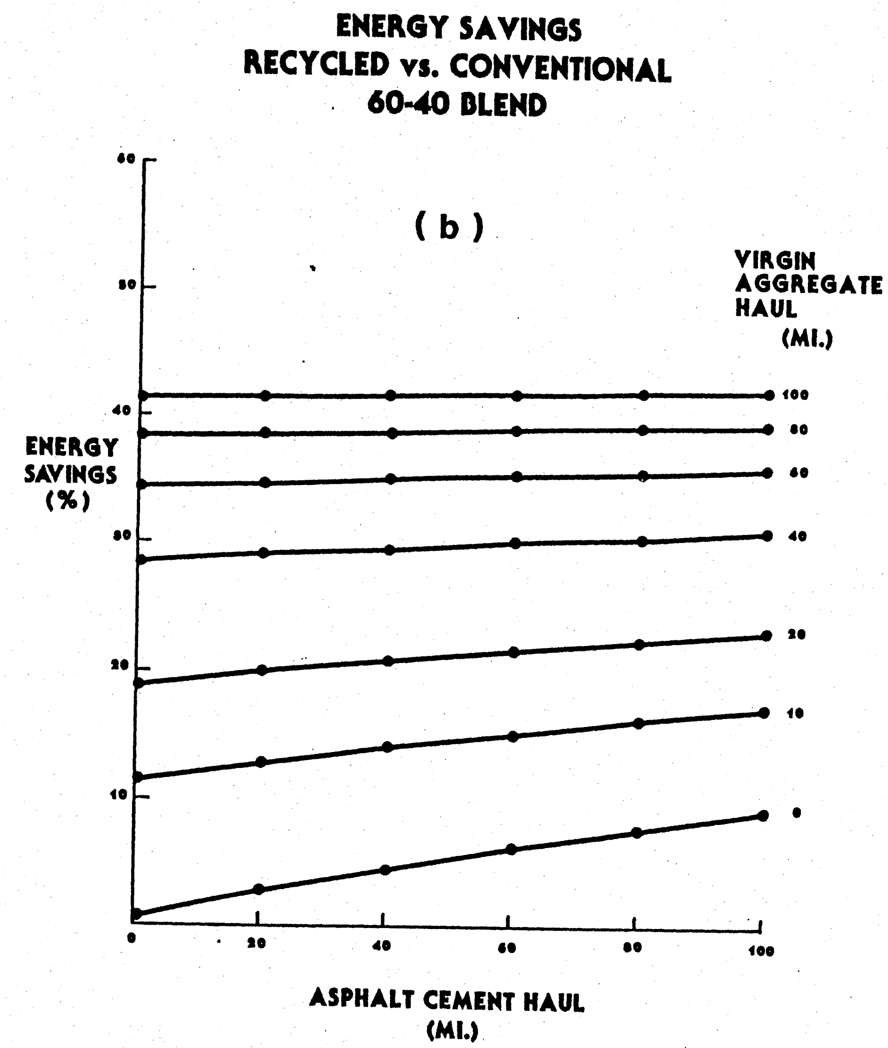


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FIGURE 5.3.- (Continued)
(b) 60-40 BLEND

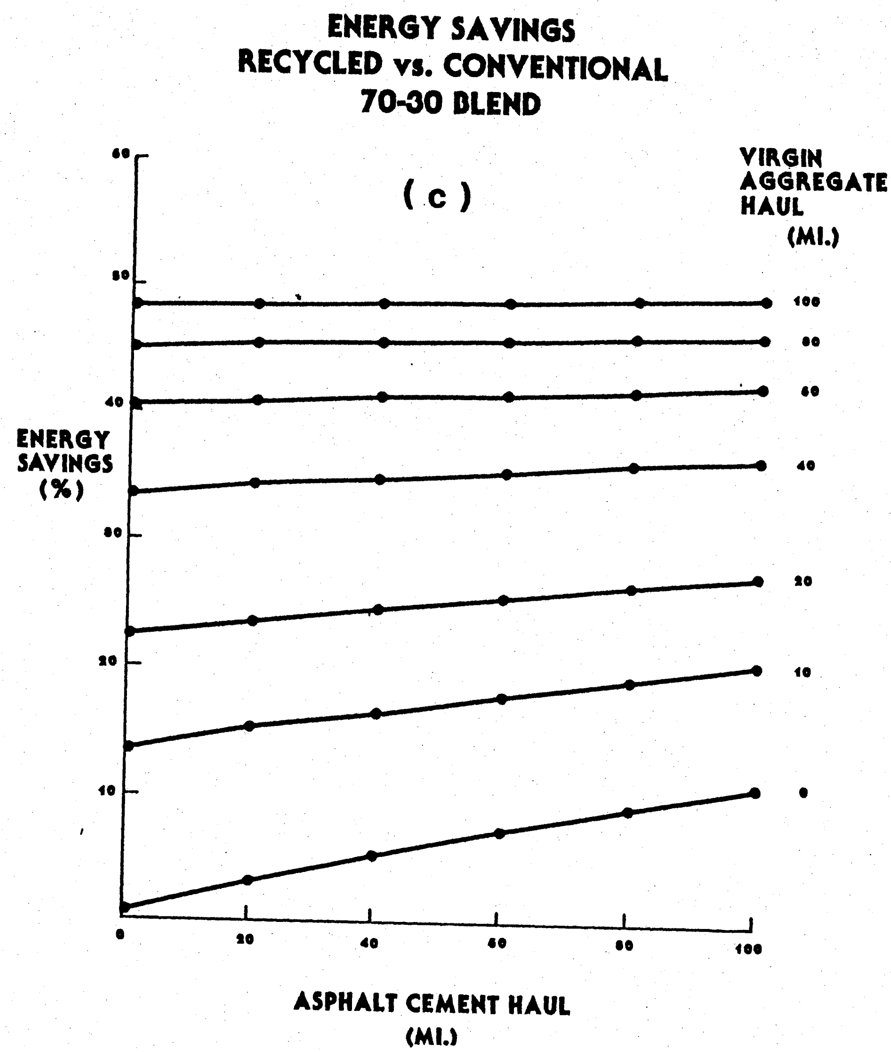

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FIGURE 5.3- (Continued)
(c) 70-30 BLEND

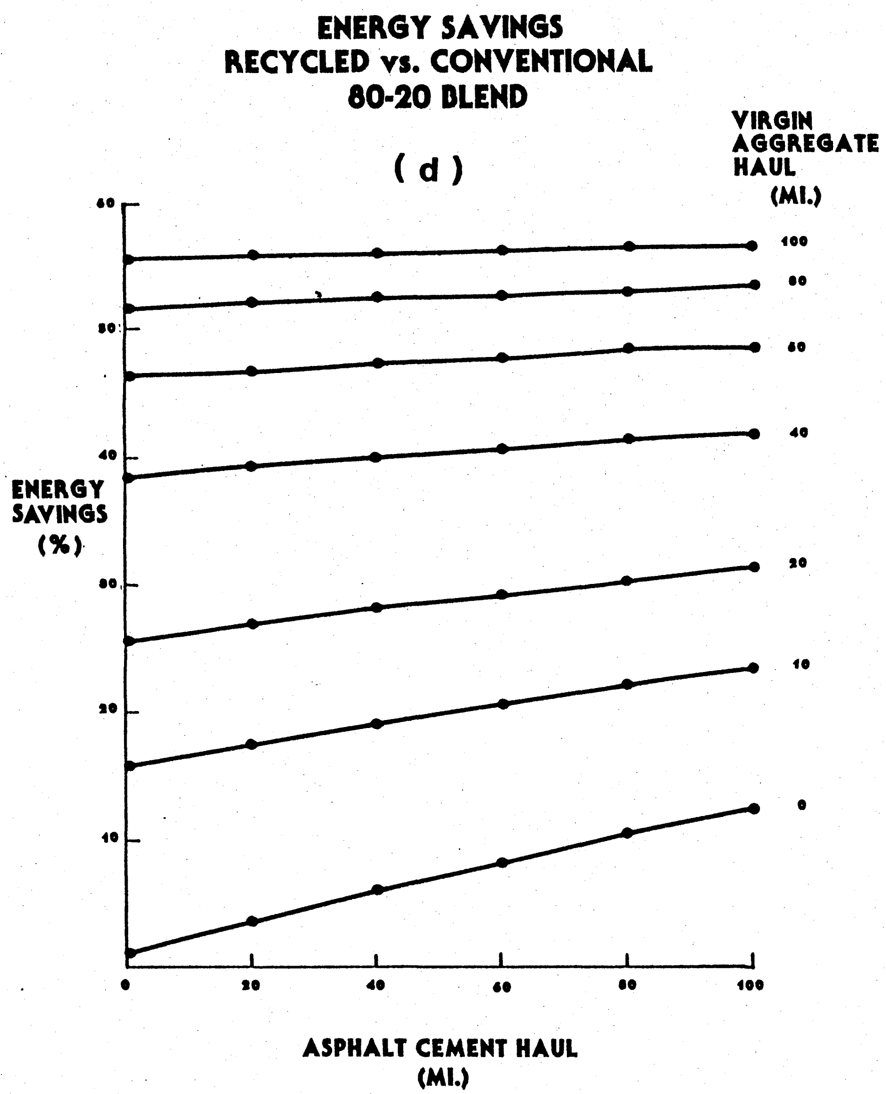

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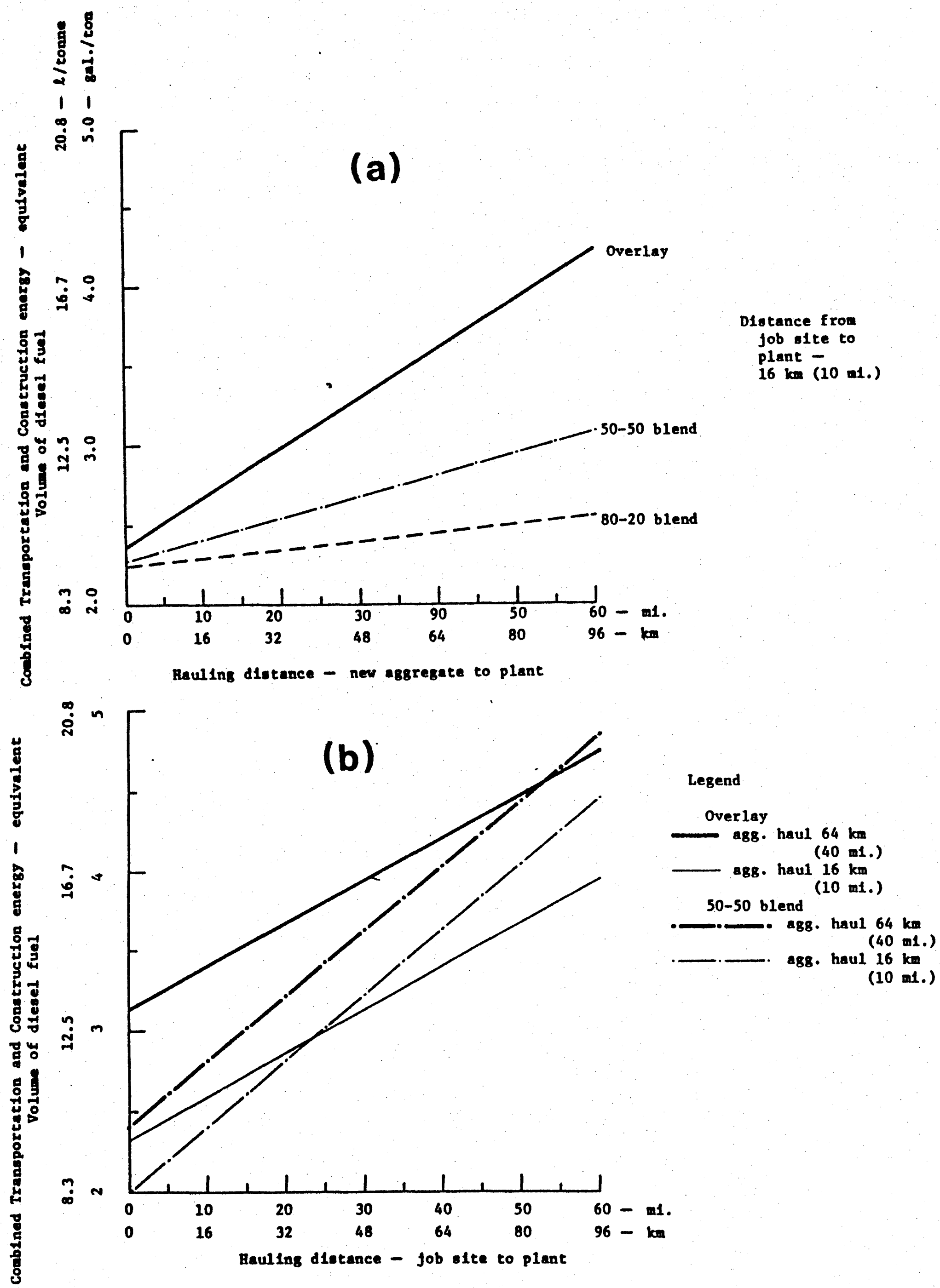
FIGURE 5.3.- (Continued)
(d) 80-20 BLEND

Figure 5.4 (a) illustrates the combined transportation and construction energy used for an overlay, as compared to that for recycling 50-50 and 80-20 blends of recycled and new material. The job site was assumed to be an average of 10 miles from the plant and the aggregate must be transported the distance indicated. A hauling distance of 60 miles for new aggregate (for example), when using an 80-20 blend of recycled and new materials, results in an energy saving of about 1.7 gallons of diesel fuel per ton of mix placed.

Figure 5.4 (b) was developed from calculations made by assuming that new aggregate was available 10 miles from the plant in one case, and 40 miles in a second case. The transportation and construction energy requirements were calculated and plotted for various distances from the job to the plant.

As can be seen, the energy advantage of recycling is lost if new aggregate is available near the plant and the material for recycling must be hauled an appreciably greater distance. As shown in Figure 5.4 (b), when the aggregate must be hauled 10 miles to the plant, any hauling distance from the plant to the job site that exceeds 23 miles results in a use of more transportation and construction energy for recycling than for an all new overlay. When the aggregate is hauled 40 miles, recycling retains its advantage until the distance between the job and the plant exceeds approximately 50 miles.



Source: Adopted from Reference 5

FIGURE 5.4.- EFFECT OF HAULING DISTANCE TO CENTRAL PLANT RECYCLING ON ENERGY CONSUMPTION (a) FOR NEW AGGREGATE TO PLANT AND (b) FOR JOB SITE TO PLANT

Halstead's [5, 94] and Brown's [103] analyses of asphalt recycling energy conservation features did not consider potential savings in processing energy from the reuse of the aggregate and the asphalt in the salvaged material. For each ton of salvaged material used, essentially 1 ton less of new aggregate must be processed and only about 2 percent of additional asphalt is required instead of about 5 percent for all new materials [5]. Nevertheless, the information available seems to indicate that savings in cost and energy can be achieved by using in-place cold recycling of old asphalt pavements.

On-site preparation or recycling is advantageous because there are no requirements for transportation energy. Efforts to improve cold milling and cold in-place recycling equipment and procedures should be continued so as to take maximum advantage of the potential for reducing transportation and construction costs and conserving energy.

5.5 - Conclusions and Recommendations

The **conclusions** to be drawn from the information presented in this discussion are as follows:

1. Cost of the new binder or recycling agent used to restore the characteristics of the reclaimed asphalt pavement material, is responsible for more than half the total cost of cold-mix recycling projects.

2. Equipment and labor expenditures account for the other half of a recycling project's costs.

3. The final cost of a recycling project is increased as more virgin aggregate is added to the recycled mix.

4. The computations of the final costs of cold-mix recycling operations are dependent on the assumptions and particular techniques adopted for each individual recycling project as well as on various traffic, weather, materials, location, equipment, and other related factors that vary considerably from place to place and from project to project.

5. Significant and rising initial savings of energy are possible using cold-mix central plant recycling when new aggregate must be hauled to the asphalt plant over increasingly longer distances. This energy conservation advantage of recycling can be lost when the asphalt pavement material to be recycled must be hauled significantly farther than new aggregate.

6. Cost reductions are not always proportional to the energy saved when using cold-mix recycling; they are influenced by the bases of comparisons. In general, the highest reductions of cost is estimated when actual costs for cold, in-place recycling projects are compared to estimates for replacing base courses with hot-mix base and asphalt concrete overlays.

7. Whether or not cold-mix recycling is cost or energy effective cannot be judged from figures given in the literature or reported here, since the level and length of service to be obtained from the recycled material are yet to be established. The various reports on life cycle and cost effectiveness of asphalt pavement cold recycling [4, 19, 95], do provide examples of the life cycle analysis technique itself but fail to use real long-term data obtained from actual work situations.

In order to evaluate cold-mix recycling as a rehabilitation alternative, the following recommendations apply:

1. The highway engineer must first inspect and sample the asphalt pavement to be recycled in order to obtain the necessary information for a sound mix design. This information would then determine quantities and types of virgin materials (if any) that have to be incorporated to the recycled mix. If there is a need for virgin aggregate to be added to the total mix, the approximate final cost of the recycled mixture can be estimated using the range of prices presented in this chapter. Usually, in cold-mix recycling there is a need for new aggregate only if the salvaged material's aggregate gradation does not meet standard specifications, or when the final recycled pavement thickness exceeds that of the existing reclaimed roadway.

2. Approximate costs associated with various procedures, equipment and other factors involved in cold recycling can be obtained by consulting the tables presented in this Chapter and elsewhere in this report.

3. Approximate total cost of the rehabilitation project can be obtained by using the range of prices shown for various thicknesses of the final recycled pavement.

4. The approximate cost of a hot-mix asphalt overlay when placed on top of the recycled base can be obtained using the information presented in this chapter.

5. Estimates of energy requirements for the recycling technique selected for a particular project can also be obtained from the various figures and tables presented in this chapter for cold in-place recycling, and for cold-mix central plant recycling.

6. It is recommended that some of the theoretical and practical aspects of the principles involved in cold in-place, surface and central plant recycling, for rehabilitating and/or maintaining heavily travelled county roads or city streets as an alternative to the usual practice of applying an overlay of all new materials, should be examined. The potential advantages of cold-mix recycling techniques in several of these situations where cost must be kept low (county and city streets rehabilitation programs, for example), have been recognized for some time and such techniques have been used else where in the country to a considerable extent.

7. Finally, it is recommended that county and city highway maintenance and rehabilitation programs in Indiana should include cold-mix recycling among the alternatives being investigated. The use of this process should not be ruled out before cost, energy and mix analyses demonstrate that other rehabilitation techniques are more viable and practical than recycling for a particular project.

CHAPTER 6

GUIDELINES FOR COLD RECYCLING OF COUNTY ROADS AND CITY STREETS' ASPHALT PAVEMENTS

Depending on the type and magnitude of the pavement deficiency, a number of conventional maintenance and rehabilitation alternatives may be considered by the pavement engineer in order to upgrade the deficient pavement to an acceptable level of service. Several recycling methods may also be considered as possible alternatives; however, unlike conventional methods which are generally well-known and widely practiced in Indiana, recycling methods have only been sporadically used to rehabilitate distressed asphalt pavements. The information collected throughout this overall study has shown that recycling, and in particular, cold recycling, is a viable alternative that can be used to upgrade county roads and city streets' asphalt pavements in Indiana.

6.1 - Introduction

The purpose of these recycling guidelines is to define evaluation and investigation procedures needed to identify possible recycling candidates, to develop a field and laboratory testing program, as well as other pertinent information based on the premise that <u>any secondary road or city street asphalt pavement in Indiana can be cold-mix recycled</u>.

The procedures outlined and presented throughout this chapter are designed and intended for a generalized approach to cold-mix recycling. These procedures should be followed as closely as practically possible, with simplifications being made when a particular project allows the highway engineer to skip and simplify some of the recommended steps of these guidelines.

6.2 - Materials Evaluation

This section covers the procedures for sampling and characterizing materials for cold-mix recycling. Considerations for the selection of new aggregate and asphalt materials are also included. These procedures have been modeled after information presented in References No. 7, 15 and 45, and after findings obtained from the studies described in previous sections of this report.

6.2.1 Pavement Evaluation and Field Samples

Visual inspection of the roadway and a review of construction and maintenance records, should be made to discover variations in the materials to be recycled. Sections of the asphalt pavement with significant differences in material composition should be evaluated as separate units.

The steps outlined in Figures 2.1 and 2.2 should be followed for the selection of the most viable recycling alternative for the particular project being analyzed. The information presented in Tables 1.1, 1.2 and 2.1 is also important in this selection process.

Representative samples from the pavement to be recycled are required for laboratory analysis. Procedures outlined in ASTM D 979 "Sampling Bituminous Paving Mixtures" [74], and References No. 3 and 15, should be followed.

The locations for sampling should be selected by random sampling techniques [62], with a minimum of five samples per mile (one per block in city work).

The thickness of the various component layers should be determined by visual analysis of the field sample. These thicknesses should be recorded.

The procedures described in Section 3.2 of this report should be followed in order to characterize the material being sampled. These laboratory test procedures are as described in the following ASTM standards [74]:

Tests on pavement cores:

ASTM D 2726: "Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface Dry Specimens".

ASTM D 2172: "Quantitative Extraction of Bitumen from Bituminous Paving Mixtures".

Tests on recovered aggregate:

ASTM C 136 : "Sieve Analysis of Fine and Coarse Aggregates".

Tests on recovered asphalt:

ASTM D 1856: "Recovery of Asphalt from Solution by Abson Method".

ASTM D 5 : "Penetration of Bituminous Materials".

ASTM D 2171: "Viscosity of Asphalts by Vacuum Capillary Viscometer", and/or

ASTM D 2170: "Kinematic Viscosity of Asphalts".

6.2.2 Reclaimed Asphalt Pavement (RAP) Material

The gradation of the reclaimed asphalt pavement (RAP) material from representative samples obtained after the cold milling, crushing or similar operation, can be determined by using the method ASTM C 136. It should be noted that the gradation of the extracted aggregate, as well as the gradation of the RAP material may be determined by the type of reclaiming process used, such as cold milling, crushing and similar, and/or by the removal speed, depth and direction of cutting (refer to Figure 2.6-c).

It was found from laboratory tests described in Section 3.3 of this report and Reference No. 104, that as long as the RAP gradation modulus (A) is between the recommended range of values: 5.00 to 6.00 (+/- 0.50), and the maximum size of the RAP is 1.1/2 inches, the performance of the final cold recycled mix would depend on other factors and not on the gradation of the RAP.

6.2.3 Reclaimed Aggregate Material

The review of the literature in cold recycling applications revealed that secondary rural roads' cold recycling often is accomplished by in-place, full-width recycling of the deteriorated asphalt pavement. This typical operation may or may not include the crushing and mixing up of some parts of the underlaying granular base çourse aggregate material.

To properly design a mix for this type or any other cold recycling operation, the aggregate and the original asphalt binder contained in the reclaimed asphalt pavement must be evaluated independently. It is therefore necessary to separate the aged asphalt from the aggregate contained in a representative sample, according to the ASTM D 2172 procedure, as described before. The two most important properties thus determined are: (a) Extracted or recovered aggregate gradation (by ASTM C 136), and (b) Asphalt content of the RAP (determined on the basis of the relative weights of the extracted asphalt and aggregate).

The quality of the reclaimed aggregate material (from extraction or in place material) depends on factors such as aggregate particle shape, type and amount of fines, and differences in absorption. Existing granular bases and unsurfaced roads throughout the State of Indiana encompass a wide variety of aggregate and aggregate-soil combinations. Although materials ranging from silty sands to well-graded, crushed stones can be recycled by the cold-mix process, certain criteria must be met to ensure success. Existing (in-place) aggregates for cold recycling must meet one of the following two criteria [45]:

(1) Plasticity Index (as determined by ASTM D 424 "Plastic Limit and Plasticity Index of Soils") [74], and the percent passing the No. 200 sieve should be less than 72.

(2) Sand Equivalent Test (as determined by ASTM D 2419 "Sand Equivalent Value of Soils and Fine Aggregate") [74], which is used to detect excessive amounts of clay, plastic fines and dust. According to the Asphalt Institute [45], in general, materials with a sand equivalent above 30 can be recycled successfully. The chance of success with materials having a sand equivalent from 20 to 30 depends upon the ability of the asphalt to waterproof the particles. Attempts to stabilize granular soils with sand equivalents less than 20 are not normally successful.

Finally, the ability of the reclaimed aggregate material to resist stripping can be indicated by the degree of particle coating test. ASTM D 1664 "Coating and Stripping of Bitumen-Aggregate Mixtures" [74], can be used for this purpose.

6.2.4 Combined and Virgin Aggregates

Combined Aggregates in the Recycled Mixture: Using the gradation of the aggregate from the reclaimed asphalt pavement, the reclaimed aggregate material (if any) and new aggregate, a combined gradation meeting the desired specification requirements is calculated following procedures outlined in Reference No. 45, pages 12 to 16.

The specification requirements should be those for aggregates typically used in standard cold-mix asphalt paving operations as listed by the "Indiana Department of Highways - Standard Specifications 1985", Sections 406 and 903.

As a practical matter, however, most cold mix recycling grading specifications (see Table 6.1-a) allow a reasonable variation in allowable gradations (see also Table 6.2), and correction by adding new aggregate is not commonly required. On the other hand, new aggregate may be needed to increase the thickness or the width of the recycled pavement. The quality of this new material should not be less than that of the standard aggregate materials specified in the "IDOH - Standard Specifications 1985", Section 902, and should meet the requirements described in the previous section (6.2.4) for Plasticity Index and Sand Equivalent tests.

6.2.5 Recycling Agents and Asphalt Materials

Selection of the type and grade of recycling, rejuvenating or softening agent for each project is important. There are numerous options among asphalt base materials, oils and modifying chemicals. However, it is the author's belief that the single most important factor in determining the type of agent to be used is the availability and cost comparison of the agents at hand.

Laboratory test results performed as part of this overall study, as well as other research works [8, 16, 19, 21, 34, 54, 76], indicated that in general, common liquid asphalt materials produced cold recycled mixtures of comparable if not better properties as mixes recycled with lesser known chemicals or modifying oils (refer to Sections 4.3 and 4.6 of this report).

TABLE 6.1.- EMULSIFIED ASPHALTS AS RECYCLING AGENTS:
(a) EMULSIFIED ASPHALTS FOR COLD-MIX RECYCLING;
(b) ASPHALT WEIGHTS; AND (c) LINEAR MEASUREMENTS
FOR FIELD APPLICATION (After Reference No. 45).

(a) GUIDE FOR THE USES OF EMULSIFIED ASPHALT

Type of Cold-Mix Recycling	Gradings	ASTM D 977 (Anionic)					ASTM D 2397 (Cationic)			
		MS-2, HFMS-2	MS-2h, HFMS-2h	HFMS-2s	SS-1	SS-1h	CMS-2	CMS-2h	CSS-1	CSS-1h
Plant mix:										
Open-graded aggregate	A, B, C	X	X				X	X		
Dense-graded aggregate	D			X	X	X			X	X
Sand	E, F			X	X	X			X	X
Mixed-in-place:										
Open-graded aggregate	A, B, C	X	X				X	X		
Dense-graded aggregate	D			X	X	X			X	X
Sand	E, F			X	X	X			X	X
Sandy soil	G			X	X	X			X	X

NOTE: Only standard grades of emulsified asphalt have been listed. For certain aggregate or climatic conditions other types might be appropriate. In such cases the emulsion supplier should be consulted.

(b) WEIGHTS OF ASPHALT MATERIALS

Type and Grade	kg/litre	lb/gal
Emulsified Asphalts	0.99	8.3
AC-2.5, AR-1000 200-300 Pen	1.01	8.4

NOTE: As the specific gravity of asphalt materials varies, even for the same type and grade, the weight relationships shown above are approximate and should be used only for general estimating purposes. Where more precise data are required, they must be computed on the basis of laboratory tests on the specific product.

The approximate data shown above are for materials at 15.6°C (60°F).

(c) LINEAR MEASUREMENT COVERED BY TANK OF ANY CAPACITY FOR VARIOUS WIDTHS AND RATES OF APPLICATION

To compute the number of linear metres (feet) that will be covered by a tank of any capacity, for various widths and rates of application, use the applicable formula:

SI Units:

$$L = \frac{C}{RW}$$

Customary Units:

$$L = \frac{9C}{RW}$$

where: L = No. of linear metres (feet) that will be covered
C = Capacity of tank in litres (gallons) (or quantity of asphalt in tank)
R = Rate of application in litres per sq. metre (gallons per sq. yard)
W = Width of application in metres (feet).

TABLE 6.2.- AGGREGATE GRADATIONS FOR COLD RECYCLING
(After The Asphalt Institute MS - 21) [45]

GRADATION GUIDELINES FOR COLD-MIX RECYCLING

Sieve Size	Percent Passing by Weight						
	Open-Graded			Dense-Graded			
	A	B	C	D	E	F	G
38.1mm (1½ in.)	100			100			
25.0mm (1 in.)	95-100	100		80-100			
19.0mm (¾ in.)		90-100					
12.5mm (½ in.)	25-60		100		100	100	100
9.5mm (3/8 in.)		20-55	85-100				
4.75mm (No. 4)	0-10	0-10		25-85	75-100	75-100	75-100
2.36mm (No. 8)	0-5	0-5					
1.18mm (No. 16)			0-5				
300 µm (No. 50)						15-30	
150 µm (No. 100)							15-65
75 µm (No. 200)	0-2	0-2	0-2	3-15	0-12	5-12	12-20

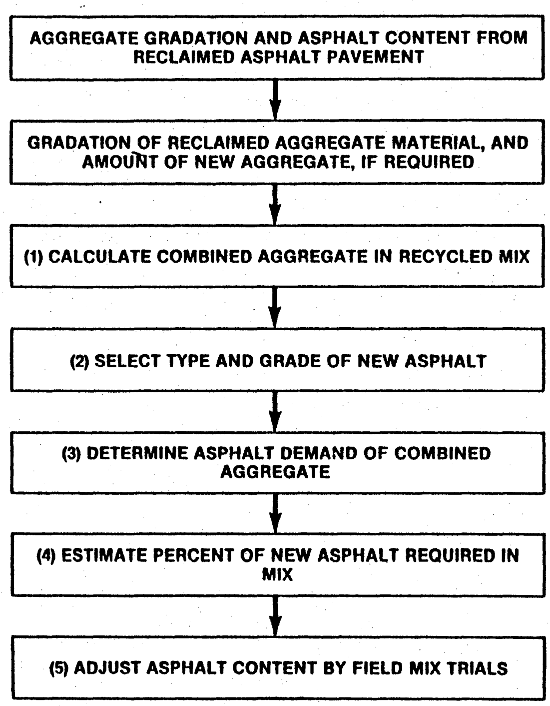


FIGURE 6.1.- COLD-MIX DESIGN PROCEDURE
(After Reference No. 45)

According to the Asphalt Institute [44, 45, 88], first consideration should be given to the type and grade of asphalt cement or emulsified asphalt that is performing satisfactorily on local projects with aggregate gradations and traffic conditions similar to those on the project under study. Additionally, standard specifications as the ones presented in Table 6.1 (a) can be used.

<u>Specifications</u> provided in the "IDOH - Standard Specifications 1985", Section 406 and 902, serve also to assist in selecting the proper asphalt material for each recycling project. Beyond the specifications, however, independent, personal judgment must be exercised in making this selection. The decision must consider usage of the complete pavement (traffic volume and loads), environmental conditions at the pavement location, type of equipment available and construction operations. This judgment is founded upon three broad engineering considerations [45]: properties of the asphalt residue, consistency, and curing or setting rate.

Asphalt cements such as AC-2.5, AR-1000, and 200-300 penetration are often used in cold-mix recycling operations. Emulsified asphalts, either medium- or slow-setting are also recommended for this type of asphalt pavement rehabilitation (Table 6.1-a). Specifications and general guidelines that apply to these asphalt materials with respect to their uses in cold-mix recycling operations can be found in Reference No. 45. Weights and rates of application for these asphalts are presented in Tables 6.1 (b) and 6.1 (c), respectively.

Finally, there are numerous and excellent references that relate with modifying oils, softening and/or recycling agents and other chemicals [3, 6, 7, 10, 15, 33, 36, 38, 49, 51, 69, 70, 71, 72, 73, 77, 78, 84, 85, 90]. In these references, agent properties, mix design procedures and other pertinent information can be found.

6.3 - Mix Design Procedures

The primary objective of the mix design for cold recycled mixtures is to produce a mix comparable to one made from all new materials. However, there is no universally accepted mix-design method for cold-mix recycling. In general, laboratory tests, empirical formulas or past experience with identical projects is used to establish the initial asphalt content with the intention of adjusting it, if necessary, after construction begins.

Mix design procedures that can be used have been presented in detail in Reference No. 104. In that report the reader can find the outline of a detailed mix design procedure recommended by AASHTO, FHWA, TRB, and others.

The Asphalt Institute [45] presents an interim design procedure as outlined in Figure 6.1 of this section. The various steps and calculations required for this particular design can be found in Reference No. 45, pages 9 to 16.

Other sources for mix design procedures of cold recycled mixtures can be found in References No. 3, 6, 7, 8, 10, 33, 47, 52, 86, and in the discussion presented in Section 2.6 of Reference No. 104. That particular section, (and Table 2.2) presents a design criteria for laboratory-prepared cold recycled mixtures. Ranges of Hveem Stabilometer and Resilient Modulus values, among others, are listed in an attempt to give minimum values of test parameters that should be met to obtain a good quality cold recycled mix.

6.3.1 Typical Indiana RAP Material - Mix Design Criteria

The findings and results obtained from laboratory test procedures (Chapter 4), undertaken as part of this overall study on cold recycled mixtures are summarized in Table 6.3. These test results were obtained for cold recycled mixtures using RAP materials obtained from typical Indiana asphalt pavements with gradations and other properties as presented in Chapter 3 (Figures 3.3, and 3.5 through 3.7), and Chapter 4 (Figures 4.1 and 4.2, as well as Tables 4.1 and 4.2).

The <u>recommended design criteria</u> based on these test results is as follows:

Test Parameter (*)	Optimum Range of Values
Density or Unit Weight:	135 to 145 pcf.
Resilient Modulus:	150,000 to 400,000 psi.
Marshall Stability:	3500 to 7500 lbs.
Marshall Stiffness:	40 to 80 lb/in $x10^3$
Marshall Index:	80 to 125 lb/in $x10^3$
Pulse Velocity:	8000 to 9500 ft/sec.

(*) Note: Test Parameters as described in Table 6.3.

TABLE 6.3.- SUMMARY OF TEST RESULTS FROM COLD RECYCLED MIXTURES USING TYPICAL INDIANA RECLAIMED ASPHALT PAVEMENTS

Test Variables	Range of Optimum Values
Mixing Water (1):	0.5 to 3.0 %
Recycling Agent or Asphalt Content (1):	1.0 to 3.0 %
Aeration Period (2):	1 hr. at 140 deg. F.
Compactive Effort (3):	Gyratory: 60 revolutions at 200 psi.
Curing Period (4):	7 days at approx. 72 deg F.
RAP Gradation (5):	Gradation Modulus ($\bar{A}$) value: 5.00 to 6.00 (± 0.50).

Note: (1): % by dry weight of RAP,
(2): pre-compaction curing in draft-forced oven,
(3): ASTM D 3387,
(4): curing out of the mold,
(5): as described in Chapter 4.

Test Parameters	Range of Optimum Values
Density or Unit Weight (6):	125.0 to 150.0 pcf.
Resilient Modulus (7):	50,000 to 400,000 psi.
Marshall Stability (8):	2000 to 7500 lbs.
Marshall Stiffness (8):	10 to 80 lb/in $x10^3$
Marshall Index (8):	55 to 125 lb/in $x10^3$
Pulse Velocity (9):	6000 to 10,000 ft/sec.

Note: (6): ASTM D 2726,
(7): ASTM D 4123,
(8): ASTM D 1559 - Modified: 72 deg. F. instead of 140 deg. F., testing temperature,
(9): ASTM D 2845.

6.3.2 Factors Involved in Cold-Mix Design Procedures

Individual laboratories have developed their own methods for determining optimum asphalt and water percentages for cold recycled mixes. In general, the initial asphalt content may be selected from experience or by some laboratory test method. These methods can be the Marshall Mix Design method or the Hveem Mix Design method as described by The Asphalt Institute MS-2 manual or Reference No. 74.

Subsequent trial batches are made with increasing quantities of asphalt and at varying moisture contents until the optimum asphalt content is determined. Ease of mixing, mixing time, percent coating and moisture content, among others, will have an effect upon the recycling agent or liquid asphalt content selected. Usually a minimum of 75 to 85 percent coating is required [44], and moisture contents will range from 0.5 to 3.0 percent [45].

6.4 - Cold Recycling Construction Guidelines and Other Considerations

Recycling as a pavement rehabilitation alternative can effectively substitute common asphalt paving construction procedures as listed in Table 6.4. There are limited construction specifications written for cold recycling but problems usually develop during the construction process. Table 6.5 lists a series of potential problem areas and the considerations and responses to be taken in order to correct them.

TABLE 6.4.- COMPARISON OF CONVENTIONAL VS. RECYCLING ALTERNATIVES FOR VARIOUS TYPES AND DEGREES OF DISTRESS - After [7].

	Rehabilitation Alternatives	
Distress Manifestation	Conventional	Cold Recycling
Alligator cracks:	Skin and permanent patches; provide drainage; thick overlay; remove &/or upgrade base.	In-place recycling.
Edge cracks:	Fill cracks; provide drainage; improve edge support.	In-place recycling.
Longitudinal cracks:	Fill cracks; overlay; reconstruct subgrade.	In-place recycling.
Transverse and Shrinkage cracks:	Fill cracks; seal coat; surface treatments.	Cold milling.
Reflection cracks:	Fill cracks; thick overlay; stress relief course plus overlay; reconstruction.	In-place recycling.
Slippage cracks:	Reconstruct.	Cold milling plus overlay.
Rutting:	Leveling course plus surface treatment or thin overlay; thick overlay.	Cold milling.
Waves:	Wedge and level; thick overlay.	Cold milling.
Bumps or Humps:	Deep patch; thick overlay; reconstruct base.	Cold milling or In-place recycling.
Shoving:	Deep patch; reconstruct.	Cold milling.
Corrugation:	Leveling course; reconstruct.	In-place recycling or Cold milling.

TABLE 6.4.- (Continued).

Chuckholes:	Skin patches; deep patches; overlay; reconstruct.	In-place recycling.
Raveling:	Seal coats; surface treatments; thin overlays; reconstruct.	Cold milling.
Weathering:	Seal coats; surface treatments; overlays.	Cold milling.
Abrasion:	Thin overlay.	Cold milling.
Bleeding or Flushing:	Hot blotter aggregate; Thin overlay (low asphalt content); reconstruct.	Cold milling.
Polished aggregate:	Seal coat; surface treatments; overlays.	Cold milling.
Structural Conditions		
All layers structurally unsound:	Reconstruct; thick overlay.	In-place recycling.
Surface structurally unsound w/ sublayers structurally sound:	Thin or thick overlays.	Cold milling plus overlay.
All layers structurally sound w/ surface functionally unsound:	Thin overlay; surface treatment; seal coat; routine maintenance.	Cold milling.
All Layers Structurally Sound With Geometrically Inadequate		
Travel Lane:	Balanced or unbalanced widening w/ new matl's.	In-place recycling.
Shoulders:	Reconstruction.	In-place recycling.
Alignment:	Reconstruction.	In-place recycling.
Cross-section:	Wedge and leveling overlay.	Cold milling.
Appurtenances:	Reconstruct.	Cold milling.

TABLE 6.5.- COLD RECYCLING CONSTRUCTION PROBLEMS AND CONSIDERATIONS (After McKinney [7])

IN - PLACE RECYCLING

Potential Problem Area	Considerations and Responses
	Ripping and Crushing
Ripped Pieces Too Big	Reduce Space Between Ripping Passes, Run Roller Over Material
Excess Fines in Salvaged Material	Limit Depth of Ripping to Pavement Thickness, Eliminate Traffic
Crushing Operation Inefficient	Feed Pieces Too Large, Reduce Feed Size
Generation of Excess Fines - Hammermill	Assume Twice Asphalt Thickness Will Be Processed
Stabilizer Shear Protection - Cobbles	Remove In Advance of Crushing
Excessive Volume of Material to Crush	Multiple Windrows
Chemical Reduction Slow Acting	Min. Air Temperature - 70^{o}F, Min Ground Temperature -60^{o}F, Keep Material Saturated
Generation of Dust, Excessive Tooth Wear	Add Moisture to Ripped Material
Excess Moisture in Ripped & Crushed Mat.	Limit Operations to One Day's Production
	Mixing
Excess Material To Be Properly Mixed	Multiple Mixing Lifts
Large Amount of Binder To Be Added	Multiple Applications, Limit To 1% per Pass, Mixing Between
Large Amount of New Aggregate To Be Added	Multiple Applications, Mixing Between Applications
Excess Moisture in Salvaged Material	Aerate Prior to Mixing, Max. Moisture 3% (Emulsions), 7% (AC)
Too Little Moisture In Salvaged Material	Add Water, Min. Moisture 2%(Emulsions), 4% (AC)
Inadequate Asphalt Dispersion	Additional Mixing Passes
Low Temperature Mixing	Limit Construction Season, Min. Air Temperature - 40^{o}F
	Laydown, Compaction & Trimming
Improper Roadway Crown	Use Paver Rather Than Blade
Excess Moisture in Mix-Improper Compaction	Aerate, Maximum Moisture - 3 to 4%
Shoving of Recycled Mix	Excess Moisture in Mix, Aerate (Leads to Strength Reduction)
Overcuring - Inadequate Compaction	Compact Within Reasonable Time
Undercompaction	No Gain In Strength With Curing - 95% Min. Compaction
Tire Tracks In Compacted Mix	Steel Wheel Roller For Breakdown Rather Than Pneumatic Tired
Curing	Delay Overlay 7 to 14 Days After Compaction

COLD SURFACE RECYCLING

Gradation of Milled Material	Decrease or Increase Milling Speed
Excessive Depth of Removal-Poor Production	Multiple Milling Passes
Generation of Large Chunks or Slabs	Leave Thin Layer of Pavement Over Base
Generation of Dust	Water on Pavement in Advance of Milling
Street Appurtenances	Identify in Advance, Remove or Work Around
Compaction of Cuttings	Sweep Immediately Following Milling
Consolidation of Stockpiled Tailings	Minimum Stockpile Height, Keep Equipment Off Pile

In general, surface recycling deals with the removal of the top few inches of pavement to correct surface defects and improper geometric alignment, removal of heavily oxidized crust layers, correction of drainage and city street curbline problems, and preparation of the surface for overlay. Surface recycling procedures are discussed in detail in References No. 3, 7, and 15, as well as in Section 2.1.2 of this report.

Recycling by in-place construction procedures entails the following general steps:

Scarifying/Ripping
Size Reduction
Mixing
Spreading
Compaction
Asphalt Surface Course or Treatment.

Scarifying/ripping, size reduction, and mixing and spreading may be accomplished singularly or in various combinations (refer to Figure 2.6-a, 2.6-d, 2.7 and 2.8), depending upon the equipment used.

The cold in-place surface and base recycling operations are as outlined in Figure 2.3, with the typical end product being a pavement such as the one depicted in Figure 6.2. Typical thickness design procedures (beyond the scope of this study), can be found in Reference No. 45, pages 19 to 28, and References No. 7, 10 and 15. Table 6.6 is included here as a reference for minimum thickness of asphalt overlay over cold recycled base courses, as recommended by The Asphalt Institute MS-21 [45].

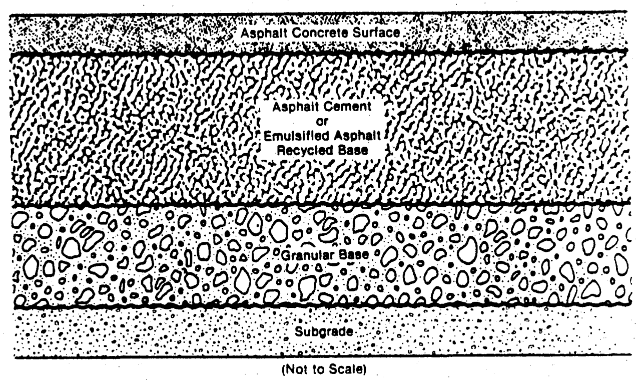


FIGURE 6.2.- TYPICAL COLD-MIX OVER OLD GRANULAR BASE
(After Reference No. 45)

TABLE 6.6.- MINIMUM RECOMMENDED ASPHALT OVERLAY THICKNESS
(After The Asphalt Institute MS-21)

MINIMUM THICKNESS OF SURFACE COURSE OVER COLD-MIX RECYCLED BASE

Traffic Level (EAL)[a]	Minimum Surface Course Thickness	
	mm	(in.)
$< 10^4$	x[b]	x[b]
10^4	50[c]	(2)[c]
10^5	50[c]	(2)[c]
10^6	75[c]	(3)[c]
10^7	100[c]	(4)[c]
$> 10^7$	130[c]	(5)[c]

[a]Equivalent 80 kN (18,000 lb) single-axle load applications.
[b]Single or double surface treatment.
[c]Asphalt Concrete or Type I emulsified asphalt mix with a surface treatment.

Since in-place cold-mix recycling construction requires that the material be placed in windrows prior to mixing and spreading, it was found appropriate to include here an example of typical windrow-asphalt applications as recommended by the Asphalt Institute MS-21 (Table 6.7). Finally, a list of commonly used compaction equipment for various stages of compaction of the cold-mixed material, is presented in Table 6.8.

As the last item in this set of guidelines for cold recycling, a brief description of some project management decisions are presented next [7].

* The operations and processes that should be planned and scheduled for <u>Cold Surface Recycling</u> are:

1. Water for dust suppression,
2. Location and/or adjustment of street appurtenances,
3. Regularly scheduled versus actual wear replacement of milling teeth,
4. Coordination of pickup and transportation of milling tailings, and
5. Street sweeping and overlay operations.

* The scheduling considerations for <u>In-Place Recycling</u> are:

1. Coordination of ripping and crushing operations with mixing operations (not necessary if one-step, single-pass equipment is used),
2. Timely supply of water for mixing and/or crushing,
3. Timely supply of recycling agent or binder for mixing,
4. Timely supply of new aggregate (if required) for mixing,
5. Proper timing of compaction operations, and
6. Coordination of recycled material curing with overlay operations.

TABLE 6.7.- WINDROW - ASPHALT APPLICATION (EXAMPLE)
(After The Asphalt Institute MS-21)

WINDROW-ASPHALT APPLICATION

01 WINDROWS—Several types of cold-mix construction require that the materials to be recycled be placed in windrows prior to mixing and spreading. If windrows are to be used, the roadway must be cleared of all vegetation to a width sufficient to accommodate both windrow and traffic while the mixture cures. Because the thickness of the new pavement is directly proportional to the amount of aggregate in the windrow(s), accurate control and measurement of the volume of the windrowed material is essential.

02 DETERMINING ASPHALT APPLICATION RATE—Before mixing operations begin, the correct asphalt application rate and forward speed of the spray-bar equipped mixer or asphalt distributor must be determined for the quantity of aggregate in the windrow. Also, when using emulsified asphalt, it is frequently necessary to moisten the aggregate before applying the asphalt and the water application rate and forward speed of the water distributor must be determined.

The following formulas can be used to find the asphalt application rate in litres per linear metre (gallons per linear foot) of windrow and the forward speed required of the mixer or distributor in metres per minute (feet per minute). The formulas also can be used to find the application rate and distributor speed for water by substituting water for asphalt.

First, determine the volume of aggregate in the windrow:

$$V_a = \frac{(A + B)C}{2} \text{ x metres (feet)} \qquad (1)$$

where: V_a = volume of aggregate in windrow, $\frac{m^2}{m}\left[\frac{ft^2}{ft}\right]$

A, B, C = dimensions of windrow, m (ft)

Then, find the application rate:

$$A_b = \frac{V_a \times W_a \times P_b}{W_b} \qquad (2)$$

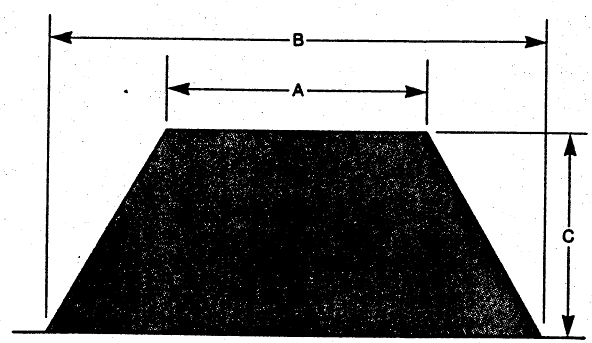
where: A_b = application rate of asphalt $\frac{\text{litre}}{\text{m}}\left[\frac{\text{gal}}{\text{ft}}\right]$

V_a = volume of aggregate in windrow (see Eq. 1)

W_a = loose unit weight of dry aggregate, $\frac{kg}{m^3}\left[\frac{lb}{ft^3}\right]$
(refer to ASTM Test Method C 29 or AASHTO T 19)

P_b = design percent of asphalt by dry weight of aggregate in the mixture expressed as decimal (refer to Chapter III)

W_b = weight of asphalt $\frac{kg}{\text{litre}}\left[\frac{lb}{gal}\right]$ (refer to Table B-1).



Volume of windrows.

To determine forward speed:

$$S = \frac{D_p}{A_b} \qquad (3)$$

where: S = forward speed of mixer or distributor, $\frac{m}{min}\left[\frac{ft}{min}\right]$

D_p = pump discharge rate, $\frac{\text{litre}}{\text{min}}\left[\frac{\text{gal}}{\text{min}}\right]$

A_b = asphalt application rate, $\frac{\text{litre}}{\text{m}}\left[\frac{\text{gal}}{\text{ft}}\right]$

TABLE 6.7.- (Continued)

EXAMPLE—A windrow of dry aggregate 0.15m (0.5 ft.) high, 1.5m (4.9 ft.) wide at the top, and 2.0m (6.6 ft.) wide at the base is to be mixed with 5.9 percent by weight of MS-2 emulsified asphalt. The loose unit weight of the aggregate is 1440 kg/m³ (90 lb/ft³). One-half of the asphalt is to be applied in each of two passes of a rotary mixer equipped with a spraying system. Needed is the total asphalt application rate and the forward speed of the mixer.

$$V_a = \frac{(1.5 + 2.0)0.15}{2} = 0.26 \text{ m}^2/\text{m } (2.8 \text{ ft}^2/\text{ft})$$

$$A_b = \frac{0.26 \times 1440 \times 0.059}{0.99} = 22.3 \text{ litre/m } (1.79 \text{ gal/ft})$$

$$\text{Asphalt application rate per pass} = \frac{22.3}{2} = 11.2 \text{ litre/m } (0.90 \text{ gal/ft}).$$

Then, the forward speed of the mixer, assuming a constant asphalt pump discharge of 100 litre/min (26.5 gal/min), is

$$S = \frac{100}{11.2} = 9 \text{ m/min } (29.5 \text{ ft/min}).$$

TABLE 6.8.- COMPACTION EQUIPMENT - COLD MIX ASPHALT BASES (After Reference No. 45)

TYPES OF ROLLERS SUITABLE FOR THE COMPACTION OF COLD-MIX ASPHALT BASES

Type of Cold Mix Asphalt Base	Stage of Compaction: Breakdown Rolling	Intermediate Rolling	Finish Rolling
Dense-graded	Steel-wheeled Pneumatic-tired Vibratory	Steel-wheeled Pneumatic-tired Vibratory	Steel-wheeled
Open-graded	Steel-wheeled*	Steel-wheeled Vibratory Pneumatic-tired†	Steel-wheeled

*Breakdown rolling of open-grade emulsified asphalt base is often facilitated by adding a small amount of detergent to the sprinkler system water to prevent pickup.

†If intermediate rolling of an open-graded emulsified asphalt base is to be with a pneumatic-tired roller, or if traffic must use a recently-placed mix, a chokestone application of from 2.2 to 3.3kg/m² (4 to 6 lb/yd²) of suitable aggregate should be applied. Stone screenings from a crushing operation or concrete sand are among those suitable.

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LIST OF REFERENCES

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VITA

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He received his secondary education in the Deutsche Schule, Santa Cruz, Bolivia; while in School, he held the Bolivian national record in high jump, and was a member of the state's track and field team. In 1975 after his compulsory military service in the Chaco border of Bolivia, he went to Santa Maria, Rio Grande do Sul, Brazil, to study in the Universidade Federal de Santa Maria, from where he graduated after 4 1/2 years with a B.S.C.E.

In September 1979 he came to the United States to study at Purdue University in West Lafayette, Indiana. He received his Master of Science in Civil Engineering in December 1981, and while pursuing his graduate studies he served as a Research Assistant for the Joint Highway Research Project, HERPICC and LARS. He also was a Graduate Teaching Assistant in the School of Civil Engineering.

He has several published papers and engineering reports to his credit. He is fluent in Spanish, Portuguese and English, and he has some knowledge of German. He is married to Julia Anne Rodgers of La Porte, Indiana, and now they have a new member in their family: Zacharias Humberto.

A copy of Reference No. 104 is available at the address listed below. The interested reader can request copies of more detailed discussions of the various topics covered in this report by writing to:

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D.B.A.
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